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**COMPENDIUM OF HUMAN RESPONSES
TO THE AEROSPACE ENVIRONMENT**

Volume III

Sections 10 - 16

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Prepared by

LOVELACE FOUNDATION FOR MEDICAL EDUCATION AND RESEARCH

Albuquerque, N. Mex.

for

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Edited by Emanuel M. Roth, M.D.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

10. OXYGEN-CO₂-ENERGY

Prepared by

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The factors determining oxygen consumption and CO₂ production of men during various tasks on Earth is covered in the first part of this Compendium, followed by data for zero gravity and subgravity environments. The second part covers the effects of the oxygen and carbon dioxide partial pressure environments on human physiology and performance in space operations.

ENERGY-OXYGEN RELATIONSHIPS

Oxygen consumption and heat production data are important in determining how much oxygen must be supplied a man for specific space missions, in designing respiratory equipment which will allow him to do heavy work, and in arranging cooling equipment which will remove the heat his body produces.

The expenditure of human energy can be monitored: (1) by direct measurement of work output; (2) by direct measurement of heat output; (3) by measuring total caloric intake and subtracting the stored amount; (4) by measuring the turnover of fuels in the body; (5) by measuring carbon dioxide production, an index of fuel oxidation; and (6) by measuring oxygen consumption (122, 181).

Direct calorimetry measures heat output as heat and requires elaborate apparatus. Indirect calorimetry depends on the calculation of heat production from the gaseous products involved in the combustion of food. (See Nutrition, No. 14.) The two methods used in indirect calorimetry are called "closed" and "open." In the "closed" method pure oxygen is breathed in a loop circuit with a spirometer wherein CO₂ is absorbed chemically and O₂ consumption is measured from the reduction in mean volume of the system. In the "open" system, breathing air, both O₂ consumption and CO₂ production are calculated from the volume and composition of expired air. This permits one to establish the ratio of CO₂ produced to O₂ consumed (Respiratory Quotient, RQ). The latter varies according to the proportion of carbohydrates, proteins, and fats participating in the metabolic process and determines the caloric equivalent per liter of O₂ consumed. For instance, at moderate activities (RQ = 0.96), energy expenditure (Q kcal/min) is calculated from O₂ consumption (\dot{V} liters/min) as:

$$Q = 5 \dot{V}_{O_2} \quad (1)$$

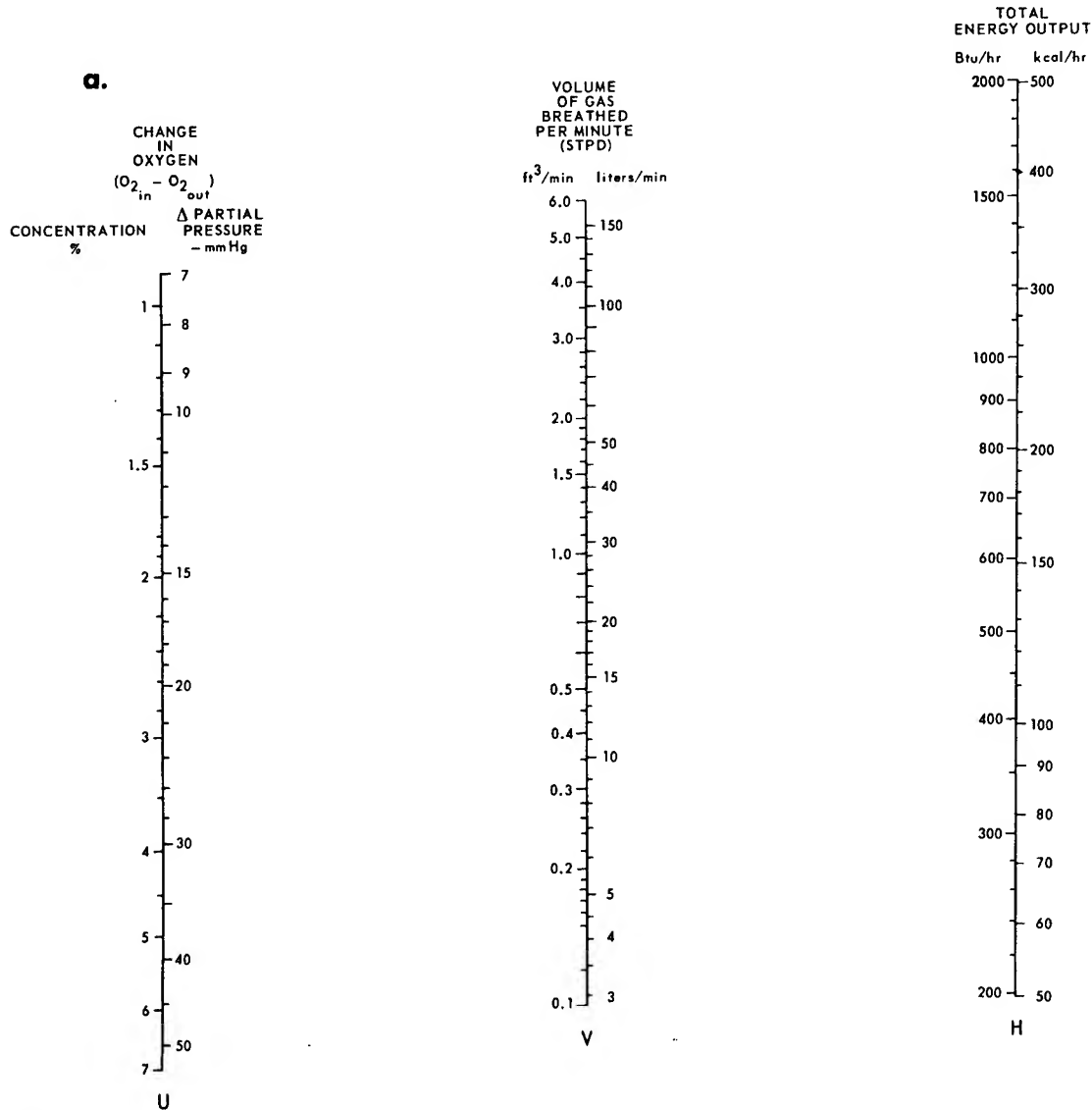
In order to perform this conversion on a molar basis, it is necessary to correct measured gas volumes to physical standards of 0°C, 760 mmHg and dry gas, expressed by the abbreviation STPD (standard temperature and pressure, dry). Figures 10-1 and 10-2 are nomograms and equations which can be used to determine interrelated metabolic data from respiratory data.

Figure 10-1

Oxygen Costs - Nomograms

(After Fletcher⁽⁸⁵⁾)

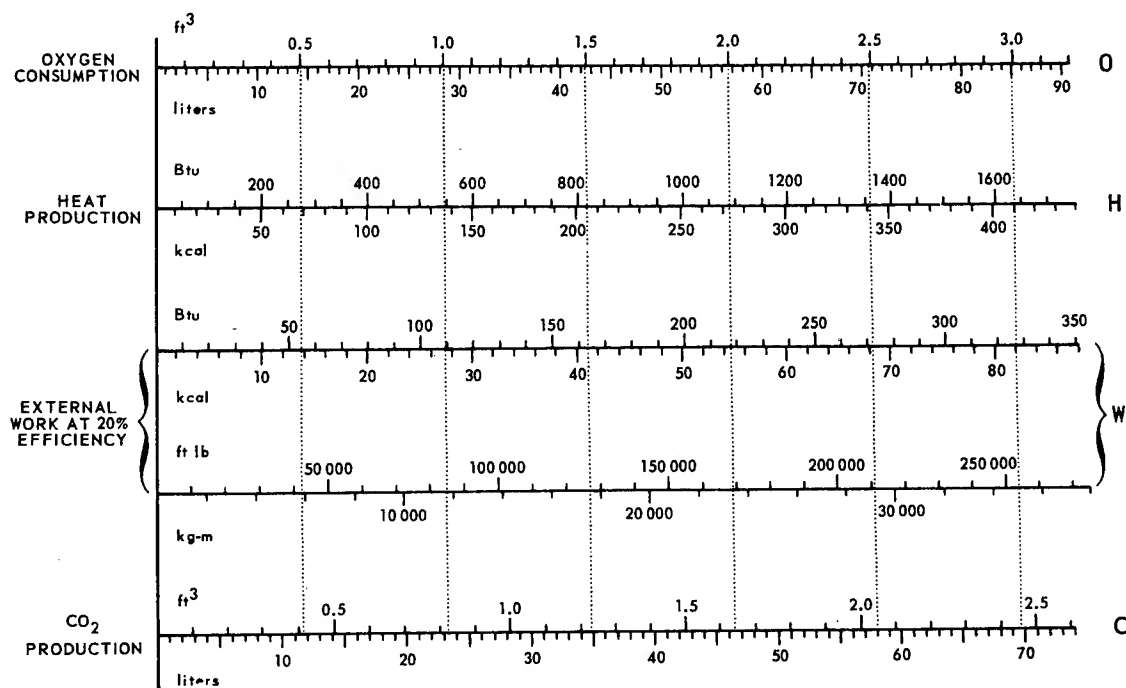
Heat output is determined from respiratory data in the following way. First, the oxygen consumption is calculated from the respiratory ventilation volume of the subject and the difference in oxygen concentration between the inspired and expired air. Second, the volume is corrected to 0°C, 760 mm Hg, dry (STPD); this is particularly important at reduced atmospheric pressures. Third, the heat output corresponding to each unit volume of oxygen is selected, either by approximation or from a knowledge of the subject's diet or from his measured respiratory quotient. For simplicity in calculation, the following two nomograms have been constructed.



Nomogram a uses the standard values: RQ = 1.00 and 1 liter of oxygen is equivalent to 5.0 kcal. It permits direction calculation of heat output (H) in Btu/hr from oxygen uptake (U) and ventilation rate (V). Alternatively, U can be calculated from H and V, or V from U and H.

Figure 10-1 (continued)

b.



Nomogram **b** uses the standard values: $RQ = 0.82$ and 1 liter of oxygen is equivalent to 4.825 kcal. This nomogram allows one to interrelate, by drawing straight vertical lines, the values for oxygen consumption (O), heat output (H), external work output (W), and carbon dioxide production (C), at typical conversion rates. Note that H may be as much as 3% lower or 5% higher than the quoted value at any specific oxygen consumption, depending on the RQ, which equals 0.7 for a pure fat diet and 1.00 for a pure carbohydrate diet. Values given in the third and fourth lines have to be modified if the efficiency changes. Typical ranges are 5 to 25%, average 20%, so that the listed work output may increase by three-quarters if the task is one that can be performed at high efficiency (e.g., bicycling). Conversely, the true value may be reduced by three-quarters if the function is inefficiently performed, e.g., high speed walking.

Figure 10-2

Oxygen Costs - Equations

(After Fletcher⁽⁸⁵⁾)

a. Formulas for calculating the energy equivalent of any given oxygen consumption:

For any gas mixture, $K = \theta \times O_{\text{cons}}$

where K is the energy expenditure,

θ is the energy equivalent per unit volume of oxygen consumed, and

O_{cons} is the volume of oxygen consumed, STPD (0°C, 760 mm Hg, dry).

If breathing gas mixtures, $K = \theta \times (O_{\text{in}} - O_{\text{out}})$

where O_{in} is the volume of oxygen (STPD) supplied to the mask, suit, or cabin, and

O_{out} is the volume of oxygen (STPD) leaving the mask, suit, or cabin.

If breathing air, $O_{\text{in}} = 20.93\%$ and $K = V(20.93 - O_{\text{exp}\%})$ with error less than 1%

where V is the volume of air (STPD) exhaled, and

$O_{\text{exp}\%}$ is the percentage of oxygen in the expired air.

Values for θ :	Pure fat diet;	}	$\theta = 525.3 \text{ Btu/ft}^3, 4.686 \text{ kcal/liter}$
	during prolonged		
	exhaustion:		
	Mixed diet:	}	$\theta = 545.0 \text{ Btu/ft}^3, 4.825 \text{ kcal/liter}$
	Pure carbohydrate		
	diet; heavy exertion:	}	$\theta = 565.8 \text{ Btu/ft}^3, 5.047 \text{ kcal/liter}$

b. Formulas for calculating gross and net oxygen costs and efficiencies:

Gross values

--below maximum
aerobic capacity*

$$C_{\text{gross}} = \frac{O_{\text{work}}}{T_{\text{work}}}$$

$$E_{\text{gross}} = \frac{W \times 100}{C_{\text{gross}}}$$

--above maximum
aerobic capacity

$$C'_{\text{gross}} = \frac{O_{\text{work}} + O_{\text{debt}}}{T_{\text{work}}}$$

$$E'_{\text{gross}} = \frac{W \times 100}{C'_{\text{gross}}}$$

Net values

--below maximum
aerobic capacity

$$C_{\text{net}} = \frac{O_{\text{work}} - O_{\text{rest}}}{T_{\text{work}}}$$

$$E_{\text{net}} = \frac{W \times 100}{C_{\text{net}}}$$

--above maximum
aerobic capacity

$$C'_{\text{net}} = \frac{O_{\text{work}} + O_{\text{debt}} - O_{\text{rest}}}{T_{\text{work}}}$$

$$E'_{\text{net}} = \frac{W \times 100}{C'_{\text{net}}}$$

Oxygen debt

$$O_{\text{debt}} = O_{\text{recovery}} - O_{\text{rest}}$$

(measured over the same time interval, which must be adequate for the oxygen consumption to return to normal)

where C_{gross} , C'_{gross} , C_{net} , and C'_{net} are rates of oxygen consumption,

O_{work} , O_{rest} , O_{debt} , and O_{recovery} are quantities of oxygen consumed,

E_{gross} , E'_{gross} , E_{net} , and E'_{net} are efficiencies (in percentage units),

W is the quantity of external work produced, and

T_{work} is the time during which work is performed.

* The maximum aerobic capacity is a characteristic measurement for each individual; it is influenced by the individual's state of training, his age (Fig. 10), and other factors.

Figure 10-2 (continued)

C. Formulas for calculating energy cost and variance of walking on a level with load

For speeds between 2.0 and 4.5 mph, the following equations give predictions for the energy cost of marching and its variance:

$$E = K + Y$$

$$K = 0.0083 (10 + W + L) e^{v/50}$$

$$Y = 0.56 \pm 0.0091 W$$

$$\sigma^2 = 0.017 e^{v/25}$$

where E = total energy expenditure in kilocalories per minute,

K = energy expenditure in kilocalories per minute above resting expenditure,

Y = resting energy expenditure in kilocalories per minute,

σ^2 = variance in K ,

W = body weight in kilograms,

L = load carried in kilograms,

v = marching velocity in meters/min, and

e = exponential constant.

Conversion factors to other units of energy are:

$$\begin{aligned} 1 \text{ kcal} &= 3.96 \text{ B TU} \\ &= 427 \text{ kgm} \\ &= 309 \text{ ft lb} \\ &= 0.00156 \text{ hp hr} \end{aligned}$$

Basal metabolic rate, measured at absolute rest in the fasting state, is commonly expressed in percent of a predicted value based on body surface area, sex, and age. The medical profession applies a time-honored "within 15%" rule to clinical evaluation of basal metabolic rates. This rule is supported by a reliability study which established a 99% probability that an individual's true basal metabolic rate will not deviate from the mean of his norm group by more than 15% (107). The Dubois (68) expression for body surface is: (Figure 10-3)

$$A = W^{0.425} \times H^{0.725} \times 0.007184 \quad (2)$$

where A = surface area (m^2)

W = weight (kg)

H = height (cm)

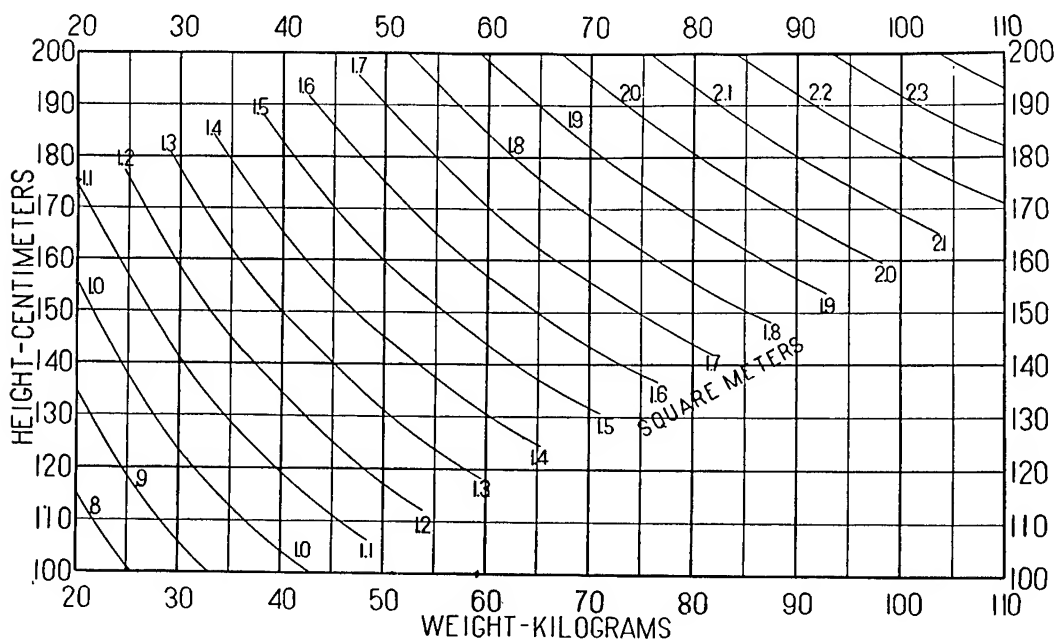


Chart for determining surface area of man in square meters from weight in kilograms and height in centimeters.

Figure 10-3

Body Surface Area Determination

(After Dubois⁽⁶⁸⁾)

For men age 35, the basal metabolic rate is given as $39.19 \text{ kcal/m}^2/\text{hr}$. Multiplying this value by the Dubois area will give a good first approximation of the BMR for a particular Astronaut.

For estimating the energy cost of various activities it is acceptable to use simplified calculations without CO_2 determinations, as presented in Figure 10-2a, with an error of less than 1%.

Energy Cost of Work

The average daily oxygen consumption on Earth for different heat outputs, body size, and diets is seen in Figure 10-4. The data for energy and nutritional requirements in orbital flight are presented in Nutrition, (No. 14). The total daily energy requirement for different operational exercise routines on Earth is presented in Figure 10-5. These are of value in estimating survival requirements in remote places on Earth.

Physical work can be generally classified as to its severity as in Table 10-6. The severity of several tasks on Earth has been classified in the same way. Table 10-7 represents the energy cost of special activities which parallel the energy costs of activity in survival situations on Earth or in driving vehicles or aircraft. Because of the modifying factors of inflated suits and subgravity

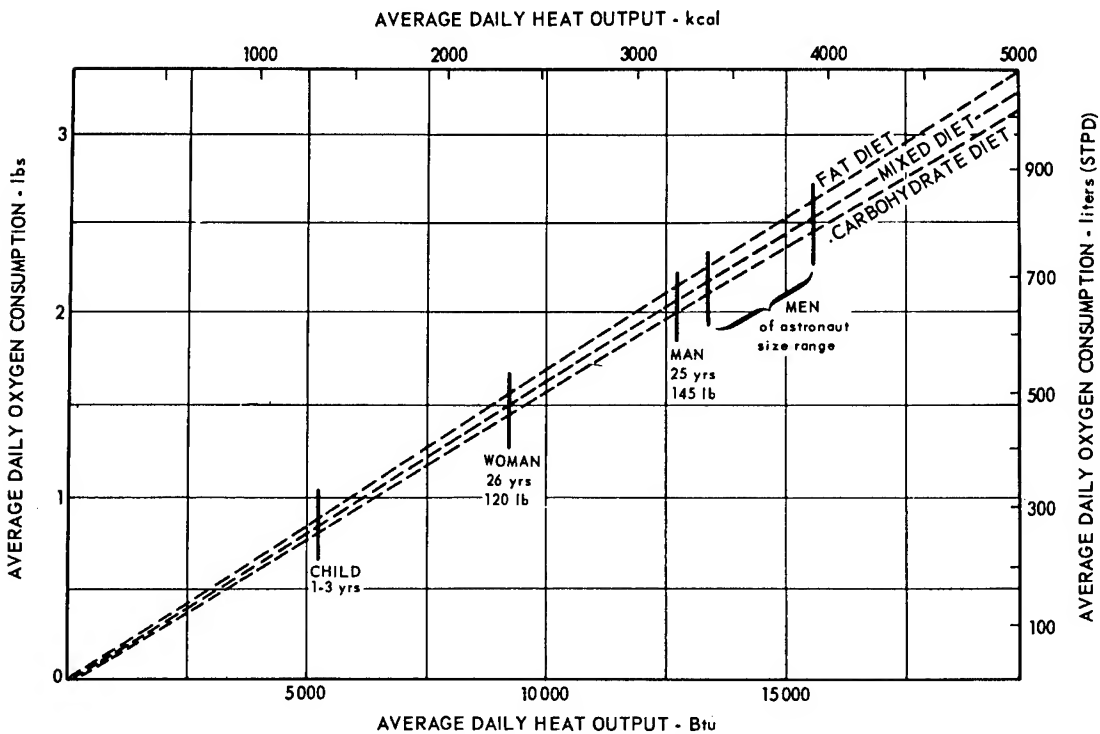
states, these energy costs should not be used directly for extravehicular operations without the approximate correction factors to be discussed below (211). Since large men consume more oxygen than small men, it is suggested that as a rough approximation for survival studies on the Earth, the values given be increased by 7.5% for large astronauts and reduced by 6% for small astronauts, based upon the size range of the men in current NASA programs. Important subject-to-subject differences exist even in men of the same size. These commonly give rise to variations as high as 60% when different men are performing the same task, as high as 30% when adjustments for body size are made, and as high as 10-15% when repeated measurements are taken on the same man.

The problem of the efficiency of energy conversion to external work is of interest (211). Factors which must be considered in appraisal of overall efficiency of performance include the rate of work, the load, the duration and quality of work, rhythmicity, and the speed of recovery in intermittent tasks. It is, of course, quite difficult to assess all these variables independently for any given task. Efficiency is expressed by the formulas in Figure 10-2b. The individual variation in mechanical efficiency for any given task is relatively small. In a review of the literature it has been suggested that during work on the bicycle ergometer the standard variation in mechanical efficiency was only $\pm 8\%$ of the found values for athletes, normal healthy people, and people with heart and respiratory troubles, provided the work level was adapted to the capacity of the individual (11).

The efficiency with which external work is produced also varies widely. It is lowest in the work of respiration (less than 5%); is 10-20% for common tasks, and highest at high work loads in bicycling and walking on the inclined treadmill (up to 26%) in trained men. When non-steady-state values for oxygen consumption are used, values up to 35 or 40% have been reported (211). Variations of these magnitudes must be allowed for in using the tables. To obtain closer estimates, measurements must be made on each astronaut in tasks closely simulating the actual task to be performed.

There are several terrestrial categories of locomotor tasks whose variables are pertinent to survival and lunar operations. These are presented in Tables 10-8 and 10-9. The effect of slope and speed which are seen in Tables 10-7, 10-8, and 10-9 are dissected in Figures 10-10 and 10-11. These data indicate the rather severe progression in energy requirement as treadmill slopes up to 25% are negotiated. The 25% slope requirement of up to 15.8 kcal/min approaches the 20.2 kcal/min for walking on the level in soft snow with a 20 kg load. From Table 10-8 it can also be seen that the negotiation of downhill slopes of 25% takes considerably more energy at 2.6 mph than does level treadmill walking at the same speed.

Oxygen cost referred to in Figure 10-10 includes the oxygen debt which is inevitably incurred in short sprints at high speed and is paid off after the event. The highest actual O_2 consumption ever reported for man is 6.17 L/min (218). More recent investigations have shown that the oxygen costs increase linearly with running speeds in the range from 150 to 360 m/min (13). The oxygen debt capacity has been found to be only slightly higher than the maximum aerobic minute value. The oxygen requirements for running a 4-min.



Body size is the most important determinant of average daily oxygen cost. This chart shows representative values for a child of 1-3 years, a woman of 25 years weighing 120 lb, and a man of 25 years weighing 145 lb. The values were calculated according to the method of the UN Food and Agriculture Organization, and assume that all three live at a mean annual temperature of 50°F and are neither sedentary nor very active. For comparison, the requirements of men of the size and age of the average of the Mercury astronauts are also given.

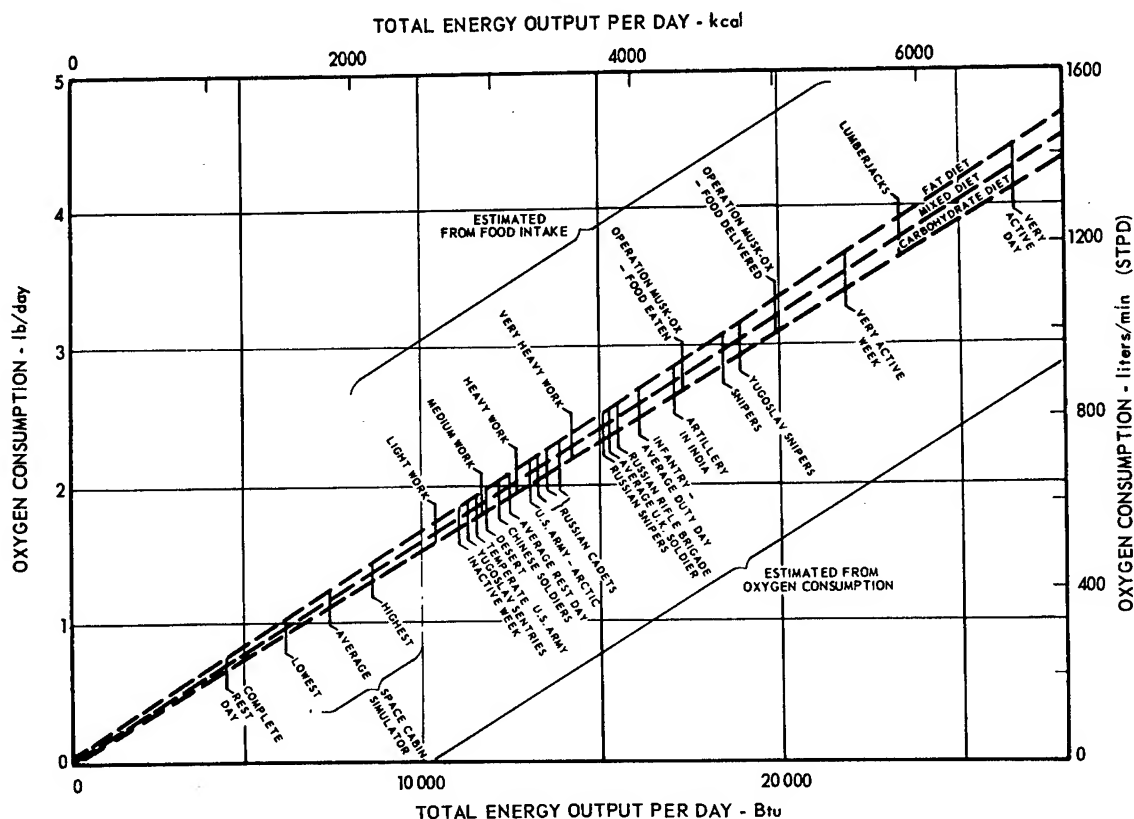
Modifications to the calculated values must be made for differences in environmental temperature. At 70°F the comparable daily expenditures, averaged over a year, would be reduced by 5%.

The three dashed lines show the values for oxygen consumption for different dietary mixtures.

Figure 10-4

Daily Oxygen Costs and Body Sizes

(After United Nations Food and Agriculture Organization⁽²⁴⁷⁾)



This chart contains data on the total daily energy exchanges of adults. Vertical axes give total oxygen consumption. Horizontal axes give total energy output.

There are two methods of calculating daily energy exchange. The preferred method is by indirect calorimetry, in which oxygen consumptions are measured and a complete time-activity study is made. Representative figures for soldiers, derived by using this technique, are given on the lower half of the diagram as an indication of the wide day-to-day and week-to-week variation within a uniform group, and of occupation-to-occupation variations.

The alternative method is by precise estimation of food intake and body weight change. Since not all food is absorbed, and since changes in body weight are not all due to energy storage or liberation, this is a difficult technique to use accurately. Representative figures obtained from food intake are given in the upper half of the diagram as an indication of light, medium, heavy and very heavy work in industry on a year-round basis. Also given are the approximate food-supply and food-eaten figures for Operation Musk-Ox, which was a 4-month, 3400-mile motorized journey across Northern Canada in winter. Long distance journeys across the moon will require special planning for food and oxygen supplies. Values obtained in space cabin simulator trials have been added as a guide to in-flight requirements. Highest values regularly recorded are for lumberjacks, whose food intake contains much fat

Figure 10-5

Oxygen Costs of Daily Routine

(After Fletcher⁽⁸⁵⁾, adapted from many sources)

Table 10-6
Classification of Physical Work by Its Severity
(After Fletcher (85), adapted from Christensen (51))

	<u>lb O₂/hr</u>	<u>kcal/min</u>	<u>Btu/hr</u>
Very light work	below 0.10	below 2.5	below 595
Light work	0.10 - 0.19	2.5 - 5.0	595 - 1190
Moderate work	0.19 - 0.28	5.0 - 7.5	1190 - 1785
Heavy work	0.28 - 0.38	7.5 - 10.0	1785 - 2380
Very heavy work	0.38 - 0.47	10.0 - 12.5	2380 - 2975
Unduly heavy work	over 0.47	over 12.5	over 2975

Table 10-7
Oxygen Costs of Special Activities
(After Fletcher (85) from many sources)

SPECIAL ACTIVITIES

	Typical values for			
<u>Engineering tasks</u>	<u>lb O₂/hr</u>	<u>kcal/min</u>	<u>Btu/hr</u>	
Medium assembly work	0.11	2.9	680	
Welding	0.12	3.0	720	
Sheet metal work	0.12	3.1	760	
Machining	0.13	3.3	800	
Punching	0.14	3.5	840	
Machine fitting	0.17	4.5	1060	
Heavy assembly work--noncontinuous	0.20	5.1	1210	
<u>Driving vehicles and piloting aircraft</u>				
Driving a car in light traffic	0.05	1.3	300	
Night flying--DC-3	0.06	1.6	380	
Piloting DC-3 in level flight	0.07	1.7	400	
Instrument landing--DC-4	0.10	2.5	590	
Piloting light aircraft in rough air	0.11	2.7	640	
Taxi-ing--DC-3	0.11	2.9	680	
Piloting bomber aircraft in combat	0.12	2.9	700	
Driving car in heavy traffic	0.12	3.2	760	
Driving truck	0.13	3.3	790	
Driving motorcycle	0.14	3.5	840	
<u>Moving over rough terrain on foot</u>				
Flat firm road	2.5 mph	0.11-0.19	2.8-4.9	660-1140
Grass path	2.5	0.12-0.20	3.2-5.1	760-1240
Stubble field	2.5	0.16-0.23	4.0-6.1	960-1440
Deeply plowed field	2.0	0.19-0.27	4.9-6.9	1160-1640
Steep 45° slope	1.5	0.19-0.27	4.9-6.9	1160-1640
Plowed field	3.3	0.30	7.8	1850
Soft snow, with 44 lb load	2.5	0.79	21.0	4850

Table 10-7 (continued)

SPECIAL ACTIVITIES (continued)

		Typical values for				
		lb O ₂ /hr	kcal/min	Btu/hr		
<u>Load carrying</u>						
Walking on level with 58 lb load, trained men	{	2.1 mph	0.07	1.9	450	
		2.7	0.11	2.9	690	
		3.4	0.18	4.6	1100	
		4.1	0.32	8.3	1980	
Walking on level with 67 lb load, trained men	{	2.1	0.09	2.3	550	
		2.7	0.11	2.9	690	
		3.4	0.20	5.1	1210	
		4.1	0.33	8.4	2000	
Walking on level with 75 lb load, trained men	{	2.1	0.10	2.5	600	
		2.7	0.13	3.4	810	
		3.4	0.20	5.2	1240	
		4.1	0.34	8.6	2100	
Walking up 36% grade with 43 lb load, sedentary men	{	0.5	0.26	6.7	1590	
		1.0	0.47	12.3	2910	
		1.5	0.62	16.0	3800	
<u>Swimming on surface</u>						
Breast stroke	1 mph	0.27	7.0	1650		
		1.13	29.0	6900		
		3.78	97.0	23100		
Crawl	1	0.35	9.0	2150		
		0.70	18.0	4200		
		1.87	48.0	11400		
Butterfly	1	0.47	12.0	2900		
		1.13	29.0	6900		
		2.92	75.0	17850		
<u>Walking under water</u>						
Walking in tank	minimal rate	0.11	2.9	700		
Walking on muddy bottom	minimal rate	0.21	5.5	1300		
Walking in tank	maximal rate	0.28	7.2	1700		
Walking on muddy bottom	maximal rate	0.33	8.4	2000		
<u>Movement in snow</u>						
Skiing in loose snow	2.6 mph	0.32	8.1	1930		
Sled pulling--low drag, hard snow	2.2	0.34	8.6	2020		
Snowshoeing--bearpaw type	2.5	0.34	8.7	2070		
Skiing on level	3.0	0.35	9.0	2140		
Sled pulling--low drag, medium snow	2.0	0.38	9.7	2310		
Snowshoeing--trail type	2.5	0.40	10.3	2460		
Walking, 12-18" snow, breakable crust	2.5	0.50	12.7	3010		
Skiing on loose snow	5.2	0.52	14.6	3800		
Snowshoeing--trail type	3.5	0.59	14.8	4200		
Skiing on loose snow	8.1	0.80	20.6	4900		
<u>Measured work at different altitudes</u>						
Bicycle ergometer	{	430 kg-m/min	720 mm Hg	0.20	5.1	1230
		430	620	0.19	4.9	1170
		430	520	0.21	5.4	1290
Mountain climbing	{	880-1037 kg-m/min	610 mm Hg	0.36-0.43	9.2-11.0	2200-2640
		566- 786	425	0.30-0.37	7.7- 9.5	1840-2260
		393- 580	370	0.25-0.41	6.4-10.5	1530-2520

Table 10-8

Energy Cost of Progression for Adult Males

(After Roth⁽²¹¹⁾, adapted from Dittmer and Grebe⁽⁶²⁾)

Activity	Subjects			Speed		Energy expenditure		O ₂ requirement, liters/min (b)	
	No.	Wt, kg (a)	Remarks	mi/hr	km/hr	kcal/min	Btu/min		
Walking, level, on:									
Hard-surface road	2	68-69	Carrying 9 kg clothing and apparatus	3.5	5.5	5.6	22.4	1.13	
Grass-covered road				3.5	5.6	6.3	25.2	1.28	
Furrow in field				3.4	5.4	7.0	28.0	1.43	
Harvested field				3.3	5.2	6.9	27.6	1.41	
Plowed field				3.3	5.3	7.7	30.8	1.57	
Harrowed field				3.2	5.1	10.0	40.0	2.05	
Hard snow	1	83		3.8	6.0	11.9	47.6	2.29	
				5.7	9.1	15.8	63.2	3.22	
Soft snow	1	83	Carrying 20-kg load	2.5	4.0	20.2	80.4	4.13	
Walking, grade, uphill	2.7%	2	70	Soldiers	3.5	5.6	6.1	24.4	(1.23)
	5.0%	1	70	Trained individual	2.0	3.2	4.1	16.4	(0.83)
	5.0%	1	70	Trained individual	2.5	4.0	4.8	19.2	(0.97)
	5.5%	1	70	Soldier	3.5	5.6	7.5	30.0	(1.50)
	6.2%	2	70	Soldiers	3.5	5.6	7.8	31.2	(1.56)
	7.3%	2	70	Laboratory workers	3.5	5.6	8.6	34.4	(1.73)
	8.3%	1	70	Soldier	3.5	5.6	9.3	37.2	(1.87)
	8.6%	2	70	Laboratory workers	2.4	3.8	7.2	28.8	(1.43)
	8.6%	64	70	1 marathon runner, 23 sharecroppers, 40 trained individuals	3.5	5.6	9.3	37.2	(1.87)
	9.0%	2	70	Soldiers	3.5	5.6	9.3	37.2	(1.87)
	10.0%	7	70	Civilian public service workers	3.5	5.6	9.7	38.8	(1.93)
	11.8%	2	70	Soldiers	3.5	5.6	11.0	44.0	(2.20)
	14.4%	2	70	Soldiers	3.5	5.6	12.3	49.2	(2.47)
Walking, grade, treadmill, uphill	0%	2	70-79		2.6	4.2	3.9-4.4	15.6-17.6	0.80-0.90
	5.0%						5.4-5.9	21.6-23.6	1.10-1.20
	10.0%						7.4-7.8	29.6-31.2	1.51-1.60
	15.0%						9.7-10.3	38.8-41.2	1.98-2.10
	20.0%						12.2-13.0	48.8-52.0	2.48-2.65
	25.0%						14.7-15.8	58.8-63.2	3.00-3.23
Walking, grade, treadmill, downhill	0%	2	70-79		2.6	4.2	3.9-4.4	15.6-17.6	0.80-0.90
	5.0%						3.4-3.7	13.6-14.8	0.70-0.76
	10.0%						3.3-3.6	13.2-14.4	0.68-0.73
	15.0%						3.7-3.8	14.8-15.2	0.75-0.77
	20.0%						4.2-4.3	16.8-17.2	0.85-0.88
	25.0%						4.8-4.9	19.2-19.6	0.97-1.00

^aValues for all subjects listed as weighing 70 kg are proportional calculations from values for subjects of other weights.

^bValues in parentheses are calculations assuming 1 liter of oxygen is equivalent to 5 kcal. The oxygen requirement per minute for a given rate of energy expenditure may exceed the oxygen uptake during any given minute if an oxygen debt is being accumulated, resulting in very high values for level running and swimming.

Table 10-9
Energy Expenditure in the Antarctic (Three Subjects)
(After Milan⁽¹⁷⁶⁾)

Age	Wt, kg	Surface area	Activity	kcal/hr/m ²	kcal/min
33	70	1.78 m ²	Walking, moderate pace, hard snow surface	147.5	4.4
			Walking, moderate pace, 6 in. new snow	192.7	5.7
			Walking up 10% grade, hard snow, moderate pace	165.0	4.9
			Walking down 10% grade, hard snow, moderate pace	163.8	4.8
33	75	1.94 m ²	Standing in cold	{ 87.4	2.8
				{ 85.8	2.8
			Walking slowly, hard packed snow	{ 150.9	4.9
			Walking, brisk pace, up 10% grade	{ 213.2	6.3
19	73.6	1.92 m ²	Walking, level terrain, hard packed snow, stopping occasionally	{ 244.9	7.9
				{ 129.7	4.1
				{ 119.8	3.8
				{ 93.8	3.0
			Walking, slow pace, subject warm	{ 110.7	3.5
				{ 153.7	4.9
				{ 130.3	4.2
				{ 130.2	4.2
			Walking up 10% grade, brisk pace	{ 192.0	6.1
				{ 218.2	7.0

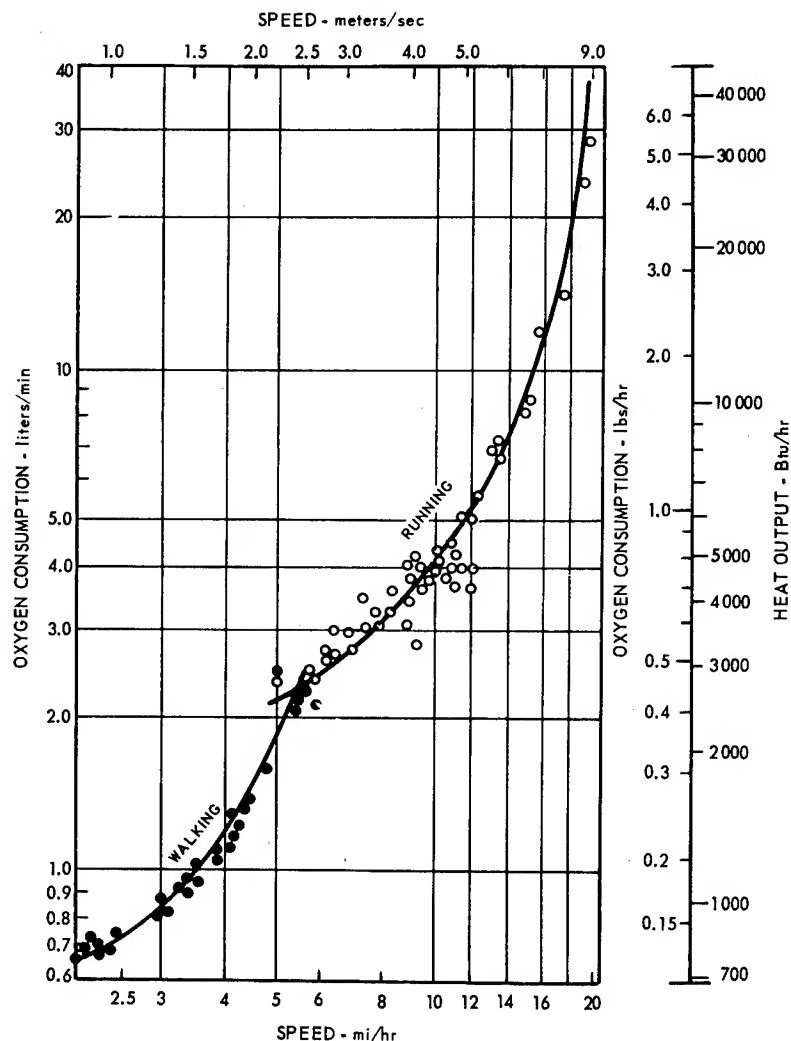
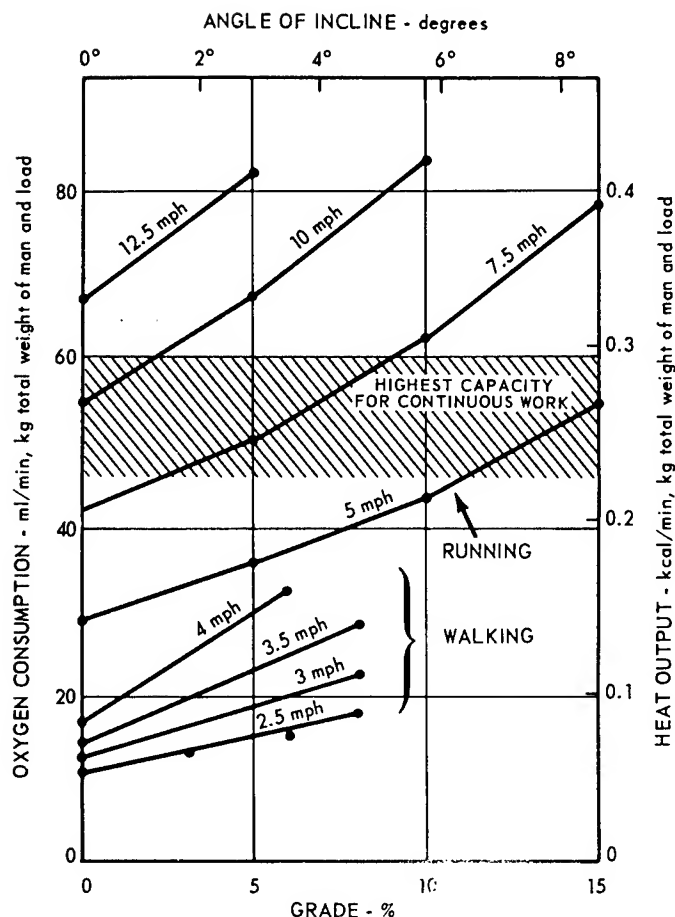


Figure 10-10

Energy Cost of Walking and Running

This chart gives the rate of oxygen cost or requirement and of total heat output as functions of speed, for men walking and running on the level, without load. Data were collected on a large number of subjects by eight authors. Heat outputs are calculated from the oxygen consumption on the basis that 1 liter/min is equivalent to 1158 Btu/hr at a respiratory quotient of 0.85. At 5 mph, the oxygen cost of walking rises above that of running at the same speed. For walking and running uphill, see Figure 10-11. Oxygen cost referred to on this figure includes the oxygen debt which is inevitably incurred in short sprints at high speed and paid off after the event.

(After Fletcher⁽⁸⁵⁾, from Dittmer and Grebe (eds.)⁽⁶²⁾)



This chart presents data for use when planning experiments on the inclined treadmill. (For level walking and running, see Figure 10-10). It permits estimates to be made of the oxygen consumption of men wearing heavy equipment, providing their capability is known in terms of speed, slope, endurance, and load carriage. Only well-trained men are capable of sustained climbing so that few men will be capable of reproducing the severer combinations.

The chart is based on extensive experiments in few subjects: in the upper segment, two middle-distance runners; in the lower segment, ten healthy male volunteer walkers. The hatched area indicates a range of values of the so-called "maximum aerobic capacity," which is approximately equal to the highest oxygen consumption that can be maintained continuously. Its value depends primarily on the body build and degree of training of the subject. The hatched area should be considered valid only for superior athletes. (See discussion of Figure 10-15.) Considerable variation must be expected, from subject to subject and from experiment to experiment.

Calculations based on the results of Åstrand (10) show that 95% of oxygen costs fall within the range of "mean \pm 8%" at values between 30 and 50 ml of oxygen per kg.

For oxygen costs of walking and running uphill, estimate per cent grade from the height of rise in 100 feet, or estimate the angle of incline from the tangent, derived from the vertical rise and the horizontal distance. Note that above the hatched area, work is exhausting, and the greater the oxygen consumption the shorter the maximal running time. Appropriate training increases both maximal oxygen consumption and the endurance time at submaximal levels, which is why long-distance cyclists, oarsmen, runners, skiers, and swimmers have outstandingly high values for both.

Equations for calculating the energy cost of load carrying and the predicted variance are given in Figure 10-2c.

Figure 10-11

Energy Cost of Walking and Running Uphill at Different Speeds and Slopes

(After Fletcher⁽⁸⁵⁾, adapted from Åstrand⁽¹⁰⁾, Goldman and Lampietro⁽⁹⁸⁾, and Margaria et al⁽¹⁶³⁾)

mile (15 mph) are 79 - 81 ml/Kg per min. The 4-min. mile is run by individuals having a maximum $\dot{V}O_2$ of 68 ml/Kg per min. The debt, therefore, amounts to $4 \times 12 = 48$ ml/Kg + 20 to 25 ml/Kg additional deficit incurred during the first two minutes of the run. Thus, the total amounts to approximately 68 - 73 ml/Kg, or for a 70 Kg runner to an oxygen debt capacity of 4.8 - 5.1 liters.

The effect of body weight on the energy for walking on the level is:

$$C = 0.47 W + 1.02 \quad (3)$$

where C = kcal/km

W = gross weight in kilograms

Formulas for calculation of the energy cost and variance of walking on the level with external loads at speeds of 2.0 to 4.5 mph are seen in Figure 10-2c. The general effect of speed on the energy of walking over the range of about 3 to 6.5 km/hr or 2-4 mph is given by the equation:

$$C = 0.8V + 0.5 \quad (4)$$

where C = kcal/min

V = speed in km/hr

As a rough estimation, it is well to know that walking on a hard level surface at 2 mph requires 2 Mets (2 times basal metabolic rate); 3 mph, 3 Mets; and 4 mph, 4 Mets + (13).

For grade walking over the range studied, the energy cost per unit weight is essentially the same whether the weight is of the body or the load (98). The pooled data from this study and the open literature were treated statistically and the following curve-fitted formula was evolved relating energy cost E for a 70 kg subject in kcal/min to progression rate V , load L , and grade G over the ranges $V = 1.5$ to 4.5 mph, $L = 0$ to 30 kg, and $G = 0$ to 9%.

$$E = 4.3 + (1.1V - 0.22V^2) + (-6.3G + 8.2GV - 0.5GV^2 + 3.6G^2V^2) + (4.06LG - 1.77LGV - 0.003LV^2 + 0.24LGV^2 - 0.06LG^2V^2) \quad (5)$$

Length of stride is also a variable to be considered. Figure 10-12 represents the caloric consumption as a function of stride and cadence for level walking.

The metabolic cost of climbing on hard or sandy surfaces is especially pertinent to the lunar surface. It should be cautioned that even the relative increase in energy cost above level walking to be seen in Figures 10-10 and 10-11 and Table 10-13 will probably not be found in suited individuals operating in 1/6th g (211). The strain of climbing sand dunes with a 40 lb pack during the heat of summer in Yuma, Arizona, as seen in Table 10-13, represents the limit of capacity at 2.5 mph for periods of 1/2 hr.

Table 10-14 indicates the energy required for going up and down stairs and ladders with variable loads.

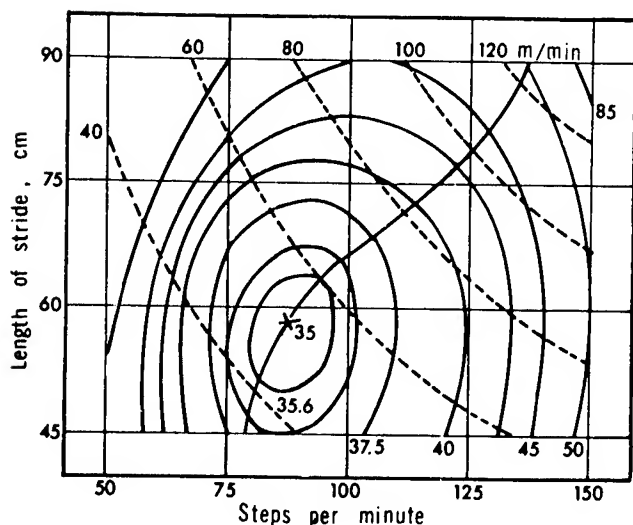


Figure 10-12

Caloric Consumption as a Function of Length of Stride and Cadence

Dashed lines represent speeds in m/min; thin solid lines (contour lines), caloric consumption; heavy solid line, optimal combinations of cadence and length of stride for various speeds¹

(After Brunnstrom⁽³⁷⁾, redrawn from Atzler and Herbst⁽¹²⁾)

Table 10-13

Energy Cost and Strain of Walking with Loads on Sand Dunes (1G)

(Adapted from Winsmann and Daniels⁽²⁶⁴⁾)

Activity	Mean kcal/m ² /hr for —			
	No load	25 lb	30 lb	40 lb
Treadmill	131	144	—	150
Level sand surface	212.2	242.6	248.5	269.6
Level hard surface	145.2	155.7	161.4	166.2
Up sand-dune slopes (2.0-2.5 mph)	282.9	333.2	320.2	346.1
Down sand-dune slopes	186.2	205.0	216.0	231.5

Activity	Mean kcal/m ² /200 yd for—			
	No load	25 lb	30 lb	40 lb
Level sand	9.13	10.58	10.83	11.34
Up sand dunes (11-12% grade)	13.30	15.74	17.00	16.44

a. Energy Cost of Walking and Carrying Pack Loads

(Speed = 2.5 mph; figures are average of four trials on each of four subjects.)

b. Comparative Energy Expenditure While Walking on Level Sand and Climbing Sand Dunes, Carrying Various Packboard Loads

Load	Mean final rectal temp., ° F		Mean final pulse rate, beats/min	
	Level sand surface	Level hard surface	Level sand surface	Level hard surface
No load	100.8	100.0	126.9	101.4
25 lb	101.1	100.1	139.2	107.7
30 lb	101.3	100.2	146.3	113.3
40 lb	101.6	100.3	160.4	128.7

c. Strain of Walking on Sand with Various Packloads

Table 10-14

Energy Expenditure Going Up and Down Stairs and Climbing Ladders with Variable Loads (1G)

(After Passmore and Drunin⁽¹⁹⁰⁾)

Ref.	Vertical speed, m/min	kcal/min for subject weighing—							
		59 kg	65 kg	69 kg	75 kg	79 kg	80 kg	83 kg	84 kg
191	14.8	6.0		8.4	9.8	9.7		9.3	
191	17.6	8.5		8.4	10.3	10.4		11.8	
66	Not stated		6.2				8.6		8.0

a. Up and Down Stairs Without Loads; Ht. of Each Stair 15.2 cm.

Ref.	Wt. kg	Height of step, cm	Vertical speed, m/min	Load carried, kg	Energy cost, kcal/min
188	63	15.2	8.2	8	8.0
				23	10.4
				38	14.2
				8	9.0
188	77	15.2	8.2	23	10.7
				38	13.2
				10	16.2
				20	19.5
126	65	17.2	17.2	40	25.2
				60	30.7

Slope of ladder, deg	Vertical speed, m/min	Load, kg	kcal/min
50	9.1	0	7.7
		20	9.5
		50	14.3
70	11.1	0	9.0
		20	11.3
		50	17.1
90	11.9	0	11.5
		20	14.6
		50	25.4

b. Carrying Loads Upstairs Only (Three Subjects)

c. Climbing Ladder⁽¹⁴³⁾; Ht. of Each Step 17 cm.

For purposes of estimating metabolic loads in the arctic conditions, several studies of sled pulling are available (253, 254). Under the most difficult subarctic snow conditions, the energy expenditure rates of over 500 kcal/m²/hr were recorded. The general relationship found was expressed by the formula (254):

$$E = 12.93 + 0.02D + 0.0119D^2 \quad (6)$$

where D = average drag in pounds

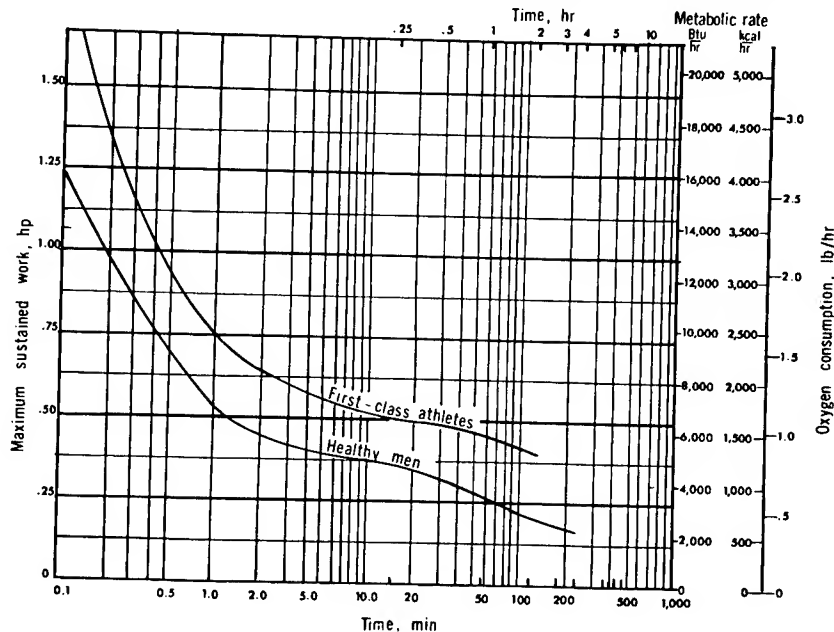
$$E = \text{kcal/m}^2 / 200 \text{ yards}$$

The predicted value for a mean drag of 17.5 pounds is 16.9 kcal/m²/200 yards. The mean value obtained for a drag of 17.5 pounds in the treadmill study, while wearing arctic ensembles, was found to be 12.16 kcal/m²/200 yards (253). Simulated sled pulling differs in at least one very important way from real sled pulling. On the treadmill the subjects walk over a smooth, non-skid rubber surface. In the field, such factors as snow depth, breakable crust, skids, and uneven walking surface are certainly responsible for part of the higher metabolic rates.

Maximum Sustained Work Capacity

In emergency situations, the maximum sustained work capacity of men is of importance. Figure 10-15 illustrates that the maximum measurable work which men can sustain until exhausted is greatest for periods of less than 1 minute (85). These are rather special data in that the kind of work is chosen to yield highest power for a given metabolic rate; hence the efficiency is 20%. Running, rowing, cycling, and cranking are the favored methods, with cycling and cranking combined showing the best efficiency. Physical conditioning is of the greatest importance, as is evident from the difference in the two curves, where, incidentally, even the "healthy men" are subjects who are young, physically active, and accustomed to the work used in the tests. Note the near plateau for the period from 5 minutes to 1 hour, showing that a superb athlete can sustain 0.5 horsepower for these times. Data beyond 1 hour are sparse, and the maximum level that can be sustained for 4 to 8 hours is not precisely known. It must be emphasized that these curves represent the very maximum levels for the most select individuals and are far above what even the average astronaut would probably be able to accomplish. The curves should, therefore, be used only as extreme upper limits of endurance.

In general, experimental studies on long-duration exercise have shown that only the well trained individual can work maximally at $\sim 33\%$ of his maximum capacity for that length of time, from day to day (13). For more "normal" people the maximum continuous working rate should not exceed 25%



The curve "First-class athletes" covers superb physical specimens and represents the very maximum attainable. "Healthy men" represents young physically active individuals accustomed to the work performed in the tests. The astronauts probably fall just below the curve for healthy men.

Figure 10-15

Maximum Sustained Work Capacity of Men

(Compiled by Fletcher⁽⁸⁵⁾ from several sources)

of the aerobic power. The best marathon runners have had oxygen intakes of 65 ml/Kg per minute for a duration of slightly more than two hours, but can not continue at this rate much longer. In "normal" well trained men -- as astronauts are expected to be -- a total energy expenditure of ~1600 kcal in 2-1/2 hours would probably lead to total metabolic exhaustion (13).

When the oxygen demand exceeds the intake of oxygen, an oxygen debt is incurred (160,164). (See Figure 10-2b.) The older literature states that the maximum oxygen debt that can be incurred for most individuals is approximately 15 liters of oxygen with values to 17 liters having been measured in a few instances (105). As indicated on page 10-7, the maximum debt recently calculated for mile runners is about 68 to 73 ml/kg or 4.8 to 5.0 liters for a 70 kg runner (13). As often done in older studies, one cannot continue recovery oxygen measurements to establish oxygen debt until the normal resting level is attained. Strenuous work aerobically performed for many hours can lead to increased basal metabolic rates for as long as an entire day: thus an increase of only 25 ml/min over the normal resting rate would amount to 36 liters of O₂ in a 24-hour period! One can hardly call this an oxygen debt -- although the excess O₂ was used for some processes which were a consequence of the severe wear and tear during the previous work period. The oxygen expenditures for sustained work above the maximum aerobic capacity of the individual can be summed arithmetically as a function of time. The time for recovery, however, is a geometrical summation and one must consider the elevated body temperature and sweat rates which may persist throughout the recovery period. The problems of determining the efficiency of repayment of this debt have been reviewed (148).

The peak energy output is dependent on age, sex, and other factors (9, 10). These studies indicate that for male subjects, maximum aerobic work capacity decreases from an average of 3.5 to 2.2 liters/min from ages 35 to 63, or by a factor of 26% (21% when calculated per kg body weight). These decrements are of value in predicting the relative work loads that older scientists may be able to undertake in future lunar missions. Individual variations due to training and general health are, of course, major factors determining these maxima. One cannot convert these oxygen consumptions directly to energy requirements since the anaerobic components of these work outputs are not clearly defined. Figure 10-16 represents a summary of the aging data for males, showing the variations expected in the athlete subjects as well as the general population (10, 238). Regular physical training can prevent a major drop of aerobic power with age. There can be no doubt, of course, that continued regular physical activity might become a problem with the increasing incidents of such ills as muscular and arthritic pains, not to mention cardiovascular and respiratory ailments. Thus, relative inactivity is frequently forced upon the aging man, and it is this inactivity which causes the loss of functional resources (13).

Typical maximum oxygen uptakes of the pilot population are reported in the treadmill study of Naval Air Cadets (238). After the usual cadet physical training program, the mean peak was 4.05 liters/min with a standard deviation of 0.39 and a range of 3.22 to 5.17, agreeing with Figure 10-16. The maximum oxygen uptake of the general Air Force population is recorded (15, 18). Figure 10-17 presents these peak oxygen consumptions as found in a treadmill

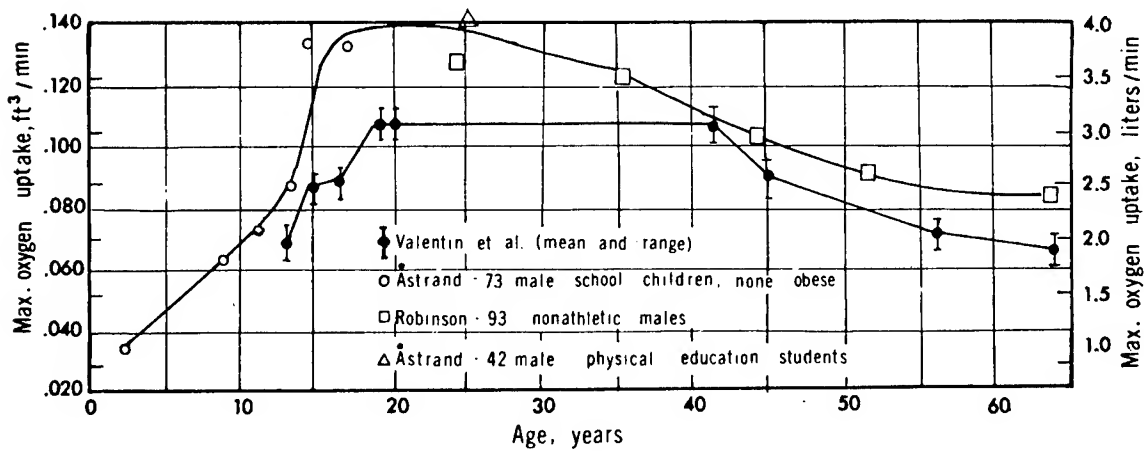


Figure 10-16

Maximum Oxygen Uptake (Aerobic Capacity) of Males

(After Fletcher⁽⁸⁵⁾, from the data of Valentín⁽²⁵⁰⁾
Åstrand⁽¹⁰⁾, and Robinson⁽²⁰⁹⁾)

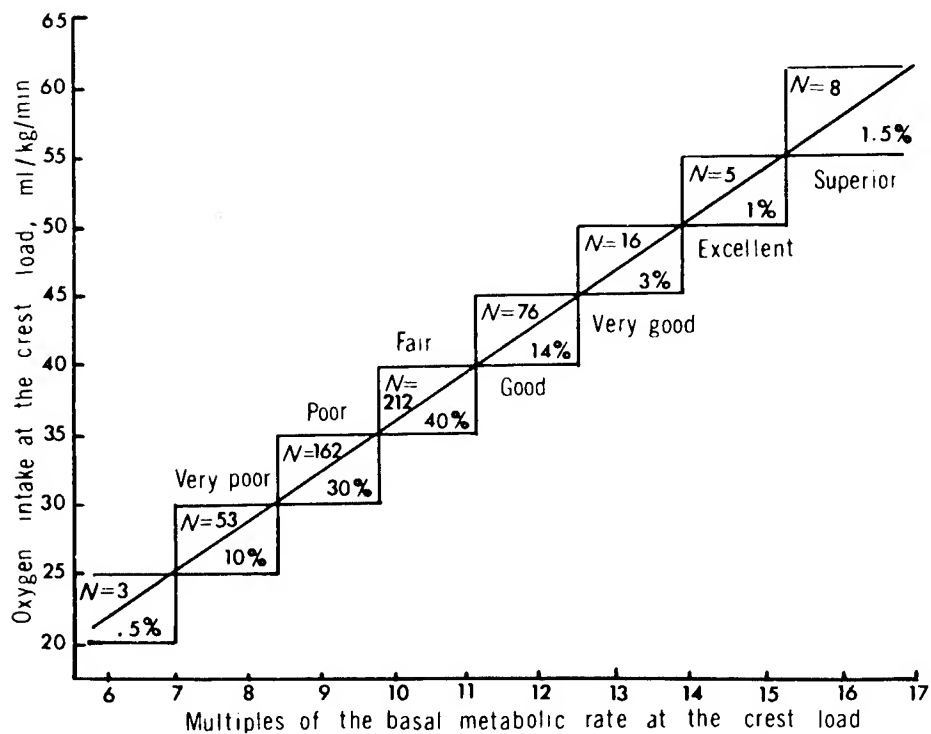


Figure 10-17

The Range of "Physical Fitness" Determined by a Standardized
Treadmill Test of 535 Male Adults

(After Balke⁽¹⁵⁾)

Table 10-18

Effect of Acute and Chronic Hypoxia on Aerobic Capacity

a. Maximum Ventilation, Oxygen Intake, and Heart Rate During Ergometer Exercise During Chronic Exposure at Various Altitudes

These men were all well acclimatized to altitude and were able to perform sustained physical exertion at 24,000 ft where an unacclimatized individual would be unconscious in a few minutes.

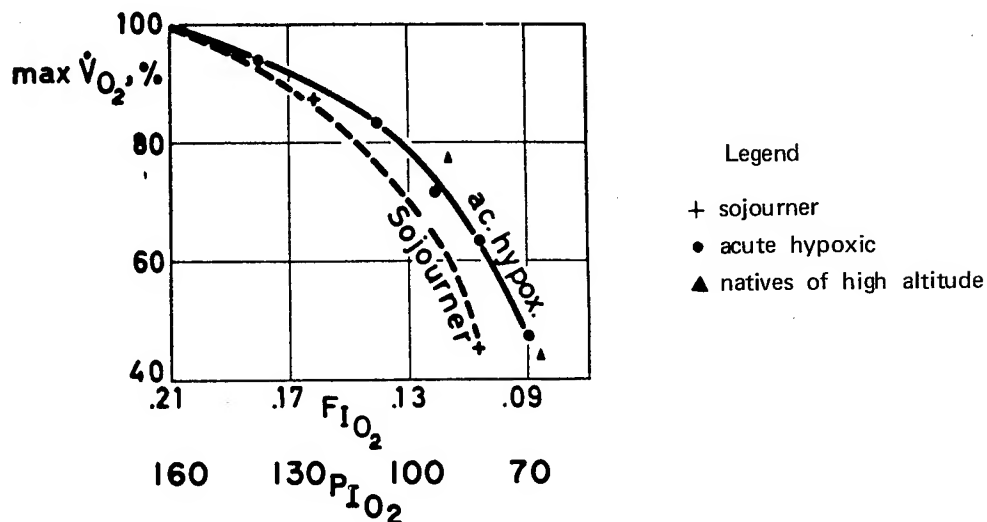
Altitude, ft	Barometric pressure, mm Hg	No. of subjects	Weight, kg	Ventilation, liters/min		Oxygen intake		Heart rate, beats/min	Work rate, kg m/min
				STPD (a)	BTPS (b)	STP, liters/min (c)	ml/kg/min		
Sea level	750	6	72.7	97.9 ± 18.4	119.7 ± 22.6	3.40 ± 0.23	46.8 ± 3.2	192 ± 6	1,500-1,800
15,000	440	5	68	75.0 ± 7.3	164.8 ± 15.9	2.58 ± 0.12	37.9 ± 1.8	159 ± 17	1,500
19,000	380	4	65.5	61.4 ± 14.3	159.1 ± 37.2	2.14 ± 0.23	32.7 ± 3.5	144 ± 13	900-1,200
21,000	340	4	65.2	56.7 ± 8.6	168.8 ± 25.4	1.95 ± 0.11	29.6 ± 1.7	146 ± 11	900-1,050
24,400	300	2	67.5	35.2 ± 2.3	119.8 ± 7.7	1.40 ± 0.09	20.7 ± 1.3	135 ± 8	600

- a. STPD = Standard temperature and pressure, dry.
 b. BTPS = Body temperature and pressure, saturated with water.
 c. STP = Standard temperature and pressure.

(After Pugh⁽²⁰³⁾)

b. Reduction of Aerobic Capacity by Hypoxia

Comparison of the maximum \dot{V}_{O_2} uptake (\dot{V}_{O_2} max), expressed as a percentage of the value observed when breathing air at sea level in acutely and chronically hypoxic individuals as a function of the O_2 fraction or partial pressure of oxygen in the inspired air.



(After Ceretelli⁽⁴⁴⁾, from the data of Margaria⁽¹⁵⁹⁾, Christiansen and Forbes⁽⁴⁹⁾, Ceretelli and Margaria⁽⁴⁵⁾ and Elsner⁽⁷⁴⁾)

test at 3.4 mph with slopes increasing by 1% each minute. The performance rating is arbitrary. Figures 10-16 and 10-17 define upper limits of aerobic capacity to be expected from select and average male populations. With no specific prior training, the mean aerobic capacity of the seven Mercury Astronauts determined on a bicycle ergometer on occasion of the selection procedure before entering the program was 2.60 Liters O₂/min. (145).

Factors Controlling Maximum Work Output

The variations in work capacity brought on by multitudes of situational factors and training have been reviewed (11). Such factors as the decreased basal metabolic rate at rest, slower pulse at rest and during exercise, increased heart volume, increased muscular mass, increased vascularization and glycogen deposition in muscles, slight increase in blood volume and decreased lactic acid level after severe work have been noted as resulting from training. The more intimate day-to-day variations in the work capacity of lumbermen have been described (149).

There are several factors modifying energy cost and maximum levels of exercise which must be considered. The first is the optimum dietary input for varied work loads. For short-term exercise such as 1/4 mile runs or 100-yard swimming sprints, no consistent advantage in efficiency is apparent for diets high in carbohydrates or proteins and fats. For prolonged exercise, however, there is some evidence of the advantage of a high-carbohydrate diet in that a subject could continue strenuous work three times as long on a high-carbohydrate as on a high-fat diet (50). Endurance was actually reduced when athletes were kept on high-fat diets for several days prior to endurance tests. From determination of respiratory quotients it was concluded that while trained athletes can utilize carbohydrate and fat indifferently during rest and light work, they increase the percentage of carbohydrate used when performing heavy work. Neither high-nor low-protein diets given over a period of 2 months affect the energy efficiency of exercise (11). No other dietary factors, given in amounts that exceed the daily minimum requirements, appear to be unequivocally ergogenic in endurance exercise (168).

The question of effect of hypoxia or supplemental oxygen as an aid to exercise tolerance has been a matter of controversy for some time. That a reduction in ambient oxygen pressure reduces work capacity is a well-studied phenomenon. The Himalayan Scientific and Mountaineering Expedition determined the graduated effects of oxygen depletion at different altitudes on men well acclimatized to these altitudes (202, 203). Figure 10-18a presents a summary of these studies. These men were able to perform sustained physical exertion at 24,400 ft whereas an unacclimatized individual would be unconscious in a few minutes! Maximum work, maximum oxygen intake, maximum ventilation STPD, and maximum heart rate declines with increase in altitude. Maximum ventilation BTPS, on the other hand, is higher at altitude than at sea level, except at the highest camp. There was no significant difference in the values obtained at heights between 15,000 and 21,000 ft (4,600 and 6,400 m). One obvious factor affecting ventilation at altitude is the reduced work of breathing air of low density. In spite of this reduction, the

ventilation BTPS fell at 24,400 ft. This result may be due to the hypoxia of respiratory muscles or a failure of subjects to exert maximum effort.

It appears that exercise at 20,000 ft (6,090 m) and above is halted by factors other than those operating at sea level. Subjectively, the overwhelming sensation which brings work to a close is breathlessness. Very high ventilation rates of about 200 liters/min BTPS - in fact, values approaching the resting 15-second maximum voluntary ventilation (MVV test) - were sometimes observed just before the breaking point at 21,000 ft (6,400 m). Subjects performing the MVV test complained of respiratory fatigue and could not keep up maximum ventilation much longer than the 15 seconds required by the test. To the conclusion that exercise at great altitude is limited by fatigue of the respiratory muscles and that extreme ventilation is the result of the low arterial oxygen tension (20 to 30 mm Hg at 1,200 kg m/min) secondary to the low alveolar oxygen, must be added that cardiac and generalized tissue hypoxia resulting from the limitation of pulmonary diffusion are probably the ultimate limiting factors at high altitude (14, 101, 102, 121, 195, 260).

For individuals not as well acclimatized, other data are available on the effect of acute hypoxia on work capacity which indicate that at an altitude equivalent of 10,000 feet (110 mm Hg P_{IO_2}) there is a 20 to 25% reduction in maximum work capacity, and at 13,000 feet, (98 mm Hg P_{IO_2}) a 33% reduction (7, 145, 205). Figure 10-18b compares the effect of reducing the fraction of inspired oxygen or P_{O_2} of the inspired gas on the maximum oxygen uptake of acutely hypoxic vs chronically hypoxic individuals (sojourners or natives). The sojourner must be at altitude for at least 5 days before such differences are noted in maximum aerobic capacity (21). The mechanism of physiologic adaptation to exercise at altitude has received much study (120, 147, 158, 258).

A question has arisen regarding the ability of hypoxic individuals to reach the same levels of anaerobic metabolism as individuals at sea level. In many studies, maximum lactate concentrations were the same at the end of exercise at sea level as at an oxygen-equivalent altitude (7, 44, 145). This suggests the same muscle lactate levels may determine the maximum effort at sea level and at altitude. However, maximum lactate levels are still a controversial issue. There are at least as many findings on lower levels of lactate. After maximal work at altitude as reports on "no change," but many of these studies involve gradual or subacute exposure to altitude as in mountain climbing (73, 120). The decrease in buffering capacity of the blood by loss of bicarbonate may affect the levels of lactate in subacute exposures to altitude of several days duration (44).

One must also consider the effect of previous hypoxia on exercise tolerance. Table 10-19 shows the effect of previous hypoxia produced by 3-1/2 hrs at 16,000 ft on the treadmill test of Figure 10-17 with a progressive increase of treadmill slope of 1% per minute at 3.4 mph. There is a distinct, if not statistically significant, evidence of a measurable reduction in work capacity correlated with the subjective symptoms. These changes, however, are not significant enough to suggest routine abortion of high-work-load missions after accidental or emergency exposure to acute hypoxia of this degree. The

Table 10-19

Effect of Previous Hypoxia on Maximum Work Capacity
(After Balke et al⁽¹⁶⁾)

Parameter	Control	Previous hypoxia	Av. diff.	Standard deviation	P value
Av. maximal O ₂ intake, ml/min	3,100	2,946	153.08	269	0.033
Optimal work capacity, m kg/min	1,091	1,054	36.92	75.18	0.06
Total test duration, min	32.8	31.0			
Time of maximal oxygen intake, min	32.0	30.5			

effect of concomitant drowsiness, headache, and sense of fatigue must be kept in mind.

The augmentation of exercise tolerance by supplemental oxygen above the sea level equivalent is still not a clear-cut picture. There have been several reports in the literature of the effects of oxygen on respiration and performance during heavy work. During moderately severe exercise, the addition of oxygen to the inspired air resulting in a marked and sudden depression of respiration has been reported (8). However, it has also been reported that no effect could be noted when 100% oxygen was substituted for air for athletic and non-athletic subjects performing moderate and severe exercise on a treadmill (19). Addition of oxygen does tend to increase the time to reach the breaking point caused by severe exercise overloads (19). It is postulated that the respiratory effects of inhaling high concentrations of oxygen were due to the abolition of an arterial anoxemia which was thought to be present when air was breathed during exercise of more than critical intensity. Relief of the anoxemia might exert its effects through the carotid and aortic chemoreceptors, or by improving cardiac function, or both. The actual cause of anoxemia in heavy exercise is still obscure. The rapid flow of blood through pulmonary capillaries may limit the time for diffusion across the pulmonary epithelium, or a pulmonary venous shunt may become effective under these severe exercise conditions. A paradoxical finding that 66% oxygen at sea level pressure will have a positive effect, but 100% oxygen, a negative effect on subjective and objective evaluation of exercise performance still requires adequate explanation (211). More work is required on this subject.

The effects of restraint and weightlessness on maximum energy output must also be considered. After a 14 day flight in Gemini 7, the time to reach the endpoint of 180 beats/min heart rate on a bicycle ergometer test with increasing load was decreased by 19 and 26% in the two pilots. There was also a decrease in oxygen uptake per kilo of body weight during the final

minutes of the test (24, 61). Bed rest studies also indicate a decrease in exercise tolerance which can be altered by various exercise regimens (30, 43, 48, 178, 179).

Carbon Dioxide reduces the maximum work capacity by increasing dyspneic response to exercise (35, 42, 83, 103, 117). (See Part B Physiology of the oxygen and carbon dioxide partial pressure environment.)

The effects of acute starvation, chronic semi-starvation in exercise capacity is covered in Nutrition, (No. 14).

The effects of hyperthermia and hypothermia (210) on the $\dot{V}O_2$ max, oxygen debt and blood lactate are found on pages 6-98 and 6-121 of Thermal Environment, (No. 6).

Work and Locomotion in Zero and Subgravity States

Energetics in Zero Gravity

The effect of zero gravity and subgravity on the energy cost of metabolism has received both theoretical and empirical study (3, 112, 114, 138, 140, 161, 206, 211, 241, 245, 266). In both cases the effect of pressurized suits must be considered. (See also sub and zero gravity in Acceleration, No. 7.)

The increase in degrees of freedom of movement in the zero gravity of orbital flight is probably a factor in the difficulty of accomplishing extra-vehicular tasks in the Gemini program (156). (See pages 7-133 to 7-158.) No specific data are available on energy consumption in orbital tasks. Gemini extravehicular bioinstrumentation consisted of only the electrocardiogram and the impedance pneumogram. These parameters had been monitored during a great many physiological and psychological tests and under widely varying conditions. The existing pool of information had reconfirmed the fact that heart rate responds to psychological, physiological, and pathological conditions. There are considerable individual variations in these responses; however, since a quantitative indication of workload actually experienced in flight appeared to be of primary importance, the feasibility of using heart rate as a quantitative indication of workload was investigated. On Gemini IX-A, X, XI, and XII, preflight and postflight exercise tests using the bicycle ergometer were performed on the pilots. During these tests, the subject performed a measured amount of work in increasing increments, while heart rate, blood pressure, and respiration rate were monitored and periodic samples of expired gas were collected for analysis. These data were translated into oxygen utilization curves and BTU plots. An increase of about 0.02 beats per minute for each work increment of 1 BTU/hr was noted for the ranges of 100 to 180 beats/minute and 1000 to 4000 BTU. Rough estimates of EVA work loads were thus attained from heart rate data, but these derived data were considered inaccurate, because changes in heart rate caused by thermal, carbon dioxide or other environmental problems could not be taken into consideration. The psychological effect of a new and different environment also could have increased the heart rates without a corresponding change in metabolic rate. Since any error

introduced by these factors would have increased the observed heart rate for a given workload level, this relationship was used for establishing maximum possible levels of work load at any instant. For instance, after evaluation of all data from previous EVA missions, altitude chamber tests, and underwater zero-g simulations, it was concluded that if the Gemini XII pilot's heart rate remained under 140 beats per minute for the majority of the EVA, the probability of successfully completing the EVA without exceeding the ELSS capabilities of 2000 BTU/hr was high. Therefore, the pilot was to be advised to slow down and rest whenever his heart rate exceeded 140 beats per minute. If his heart rate exceeded 160 beats per minute, he would be advised to stop all activities.

Periods of exercise were included in both of the standup EVAs. These exercises consisted of moving the arms away from the neutral position of the pressurized space suit. Both arms were brought from the neutral position to the sides of the helmet once each second for 60 seconds. An attempt was made to correlate heart rate data during these inflight exercise periods with preflight exercise tests. When compared in this manner, no significant difference appeared in the response to exercise performed before and during flight. It must be remembered, however, that only qualitative conclusions can be drawn from these data. Valid quantitative conclusions must await the results of more precise inflight medical experimentation in which controlled conditions and additional data collection are feasible.

Several other factors were significant in the energetics aspects of Gemini EVA. One of these was the art of conserving energy as demonstrated in Gemini XII. The pilot of Gemini XII was able to condition himself to relax completely within the neutral position of the space suit. He reported that he systematically monitored each muscle group. When a group of muscles was found to be tense while performing no useful work, he was able to relax these muscles consciously. All of his movements were slow and deliberate. When a task could be performed by small movement of the fingers, he would use only those muscles necessary for this small movement. This technique of conserving energy contributed to the low indicated work levels in the Gemini XII umbilical EVA.

For the final Gemini XII EVA, the oxygen allotment for umbilical EVA was 25 pounds, with 2.9 pounds scheduled for egress preparation and 22.1 pounds for a projected 2-hour and 10-minute EVA time line. From the experience of the Gemini XI pilot at the Target Docking Adapter (TDA) of the GATV, the use of the medium-plus bypass flow mode was planned for all TDA work. This mode increased dry makeup oxygen flow to the ELSS chestpack and increased the capability of the ventilation gas to remove latent heat and to purge carbon dioxide from the helmet. If work loads exceeded the design limits, medium-plus-bypass flow would provide greater protection against visor fogging than that obtained in the normal high flow mode. The pilot elected to remain in the high flow mode for the entire hatch-open period because of the satisfactory cooling and the absence of visor fogging. The pilot stated that he felt that his work rate had not taxed the capability of the system in the high flow mode and that he could have worked somewhat harder without discomfort. Total ELSS oxygen usage for the 126-minute EVA period was 18.9 pounds, which indicated a usage rate of 8.9 lb/hr, as compared to

the measured value of 8.5 lb/hr obtained during preflight testing. The EVA pilot performed several tasks intended to evaluate any forces acting on him from either thrust or pressure forces from the ELSS outflow. He reported that he was unable to detect any forces which might be attributable to the ELSS. There was no noticeable float-out or float-up tendency when he was standing in the cockpit with the hatch open. Study of oxygen consumption in Apollo is planned (171).

As its functional utility in performing work, traction serves as the primary source of the counter force (counteractive or reactive force) during the accomplishment of work (267). If the counteractive force is reduced, then according to Newton's third law, the amount of work that can be accomplished must also be reduced. If, however, the task is constant and the tractive environment is altered to a point such that the normal counteractive force supplied by traction is less than the work to be done, then either the task cannot be accomplished or a supplemental source must be found for the counter force. In reduced gravity environments, supplying a supplemental counter force is achieved by several means. The most common technique for both 1-g and weightless situations is the use of one arm for accomplishing the task while the second arm provides the means of transmission of the reactive force to a load sustaining object, e.g., the spacecraft. Other means of accomplishing this load transmission are by using various tethering systems, wedging the body into an opening, and using the skeletal structure in combination with a tether in the "lineman's position." (269)

The alteration in metabolic rate for the accomplishment of a given task in weightlessness should reflect the additional energy required to supply the reactive force by means of the musculoskeletal system over and above the energy required for the task itself. When aids are not available for the transmission of the necessary counterforce, the work cannot be done. Subjects at simulated lunar gravity conditions could not exert a lateral force of 15 ft-lb while pulling a cable to lift a weight (267). In addition to supplying the necessary reactive force for work at 1 g, traction also allows the storage of torsional forces during some forms of work. These stored torsional forces are important in many types of work because they aid in restoring the body to the pre-work position. As traction is reduced, the availability of this form of energy for restoration of body position decreases. Consequently, the energy required to regain the pre-stroke work position increases as traction decreases.

The energy balance for upper torso work under all tractive conditions may be expressed by the following equations relating energy, Q , and efficiency, E : (267)

$$\Delta Q_m (E) = Q_w \quad (7)$$

or

$$\Delta Q_m = Q_w + Q_{wc} + Q_{wr} + Q_s + Q_n \quad (8)$$

Where ΔQ_m is the metabolic cost of work, Q_w is the amount of energy utilized in performing useful work, Q_{wc} is the energy spent in supplying the counteractive force, Q_{wr} is the energy required to restore the body to the prework position, Q_s is energy stored as body heat, and Q_n is the net heat loss. As traction is reduced for a given task, the muscular energy required to supply

the counter force must increase to maintain the mechanical conditions necessary to accomplish the work. In other words, the total energy required to accomplish the same task is increased as traction is reduced. Since the efficiency of work is $E = Q_w / \Delta Q_m$, this is equivalent to saying that the efficiency of work is reduced as traction is reduced.

Ground-based simulation has pointed out the effect of a tractionless environment and freedom of movement on energy costs (71, 72, 199, 241, 245, 267). Figure 10-20a and b represent the increase in horsepower output and energy cost for a reciprocating stroke task when the degrees of freedom are increased on a simulator in a 1 g environment. It is of great practical importance that several groups have recently found that most reciprocating arm tasks on zero gravity simulators with 5-6 degrees of freedom require from 30 to 50% more energy than the equivalent task of 1 g when bracing is limited to one free hand (245, 266). Additional points of bracing eliminate almost entirely the excessive energy requirement for the tasks. In a self-paced operation in zero gravity simulation, there is usually an increase in the time required for a given reciprocating task of about 50%. Table 10-26a summarizes more data on the effect of reduced gravity on energy requirement for different tasks.

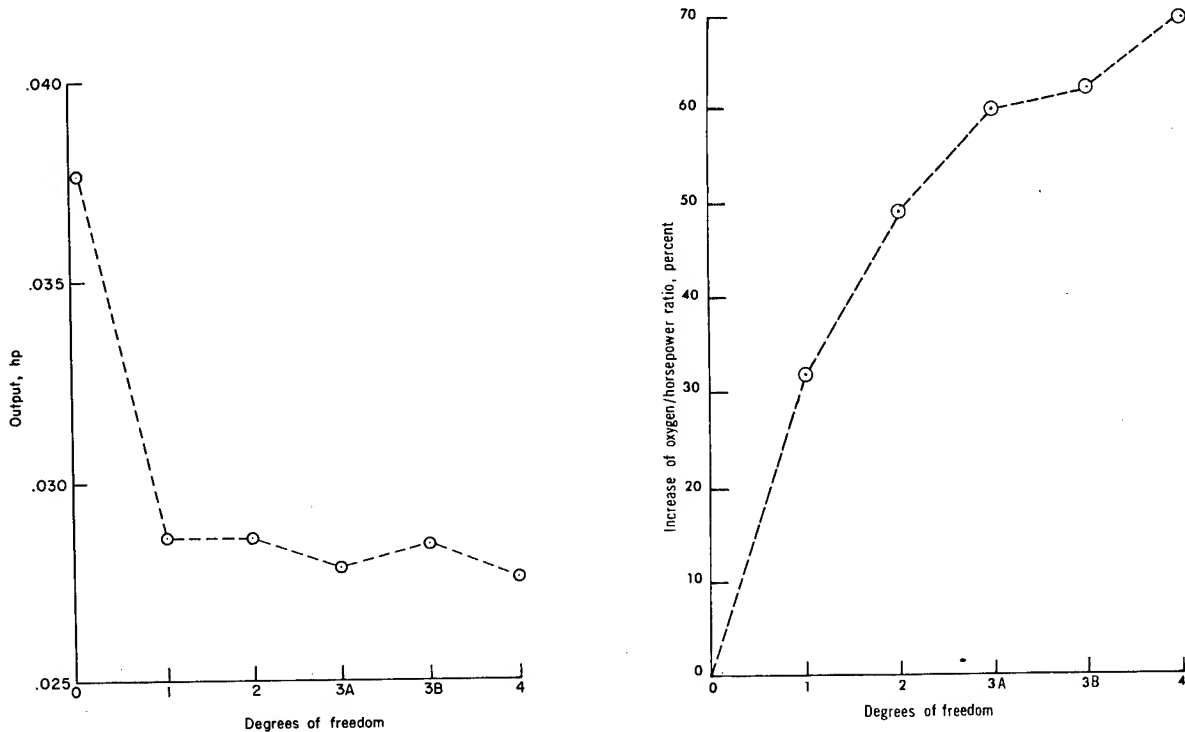
Torque tasks during simulation of zero gravity also point to the requirement for special bracing and traction devices (71, 72, 266, 268). The maximum torque which can be impulsively executed without special bracing is drastically curtailed (244). Because of inertial coupling in the multiple degree of freedom simulators, exact quantification of the torque problem is not available. As was evident in the Gemini series, torque tasks in orbit appear much more difficult than similar tasks in parabolic flight simulation (156). Underwater simulation appears to be a better approach to the problem. (See EVA of the Gemini Program, pages 7-133 to 7-156 in Acceleration, No. 7.)

In a recent study, the metabolic rates on a six-degree-of-freedom, gimballed simulator and underwater simulation were compared (268). Subjects performed typical construction and maintenance tasks discussed on pages 7-173 and 7-176 of Acceleration, (No. 7). The metabolic rates for 2 subjects are compared in Figure 10-20c. It is evident that there is a simulation effect on the data obtained. For example, the resting rate in zero-g is less than one-g, which is less than the neutral buoyancy values. The lower zero-g values are probably the result of the men being completely supported so that the metabolic cost of maintaining balance and posture were not factors in determining the total metabolic rate. The additional metabolic cost in the one-g simulation represents the additional cost of the use of postural muscles and a greater heat load. The twofold increase of resting rates noted with neutral buoyancy results from the subjects' having to exert a reactive force to maintain balance and position during the simulation and the temporal error induced by the long sample lines used in the underwater simulation. Details of techniques used in the simulation are available (268).

The maximum metabolic rates noted during the studies are recorded in the second column of Figure 10-20c. The high peak values of the zero-g simulation result from the high cost of providing the reactive force necessary to accomplish any task. Throughout these work sessions the subjects complained

Figure 10-20

Metabolic Costs of Work During Simulation of Weightlessness



a. Horsepower Output with Various Degrees of Freedom on Reciprocating Task; 15-Pound Load and 22-Inch Stroke

b. Percentage Increase of Oxygen/Horsepower ratio for a Reciprocating Task; 15-Pound Load and 22-Inch Stroke

Effect of degrees of freedom on power output and oxygen efficiency of output in a mechanical weightlessness simulator.

2 df - Subject free to translate horizontally in all directions.

3 dfA - Subject free to translate horizontally in all directions and rotate in a vertical plane.

3 dfB - Subject free to translate horizontally in all directions and rotate in a horizontal plane.

4 df - Subject free to translate horizontally in all directions and to rotate about his own center of gravity in planes parallel and perpendicular to the floor.

(After Streimer et al⁽²⁴⁵⁾)

c. Comparison of Metabolic Rates During Construction and Maintenance Work (Btu/hr)

Simulation	Rest	Maximum Measured
One-g	697	3243
Neutral buoyancy	1035	2170
Zero-g six-degree-of-freedom	478	3489

(After Wortz et al⁽²⁶⁸⁾)

of not being able to achieve and maintain a desired position, and had to exert a tremendous effort to accomplish even a simple task. It is interesting to note that the highest metabolic rates were measured during the maintenance tasks and particularly with the removal of a maintenance box. This resulted from problems in positioning to reach the retaining bolts. Filing, drilling, and sawing were also major problems in the zero-g configuration.

The lower peak values seen with the underwater studies are complicated by several factors. It is probable that the thermal loss of the subject is increased and results in lower metabolic rates. There also exists the effect of the drag introduced by the water medium, and also the relative ease with which the subject could bend the suit in the water medium as compared to an air environment. The role of thermal exchange and bending forces in the suit are areas which require clarification in future studies. It should be noted that the greatest portion of the decrease in metabolic rates is probably due to the subjects' being able to take better advantage of their restraint systems during underwater simulations.

In general, metabolic rates remained below 2000 BTU/hr regardless of simulation techniques. Heart rates were never greater than 140 beats per min during underwater tests, and thus compare with those seen on Gemini XII (156). The highest heart rates were noted during zero-g simulation where they reached 155 beats per min during a drilling exercise. Heart rates did not exhibit a linear correlation with metabolic rates in these tests. This indicates that metabolic rates cannot be derived from heart rate for this type of simulation. Sweating was a major problem with all modes of simulation and work tasks. Start of sweating could not be correlated with metabolic rates. This points to the need for body core temperature measurements and study of thermal exchange with the atmosphere to evaluate sweating, metabolic rates, and work during these simulations. Respiratory rates showed no correlation with activity. Tests with a system which isolates the respiratory gases from suit flow are necessary if real-time data are to be obtained which can be correlated with work modes. A mathematical model of the human bio-mechanical function is being developed to be used in conjunction with future metabolic studies of this type (268).

Energetics in Space Suits and Lunar Gravity

Non-locomotor tasks in lunar subgravity conditions must be considered with and without inflation of space suits (199, 236, 267). With only single free-hand fixations, reciprocating tasks require about 20% more oxygen consumption under 1/6th g simulation than under 1 g (211). Figure 10-26a presents data on effect of g-level on the energetics of different tasks. The presence of an inflated space suit adds considerably to the energy requirements for specific tasks as seen in Tables 10-21 and 10-22. Computer programs are being prepared for analysis of space suit and 1/6th g interactions in task analysis (138, 139, 140).

The energetics of locomotion on the lunar surface is a multivariate problem which has still not been adequately solved (67, 112, 114, 140, 161, 204, 206, 211, 267). Simulation appears to be the major difficulty. Several parameters, such as gait, traction, and limb segment velocity are relevant.

Table 10-21

Metabolic Rate in Pressure Suit Operations

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR			Number of Subjects	Vent Flow CFM	Trials
			15 Mins	30 Mins	60 Mins			
Treadmill	Street							
0.8 mph	Clothes	0.0	510	576	562	5	—	20
0.8 mph	Gemini	0.0	—	811	780	3	11.5	4
	(G-1c-4)	3.7	—	1159	1171	3	11.5	4
1.5 mph	Gemini	0.0	—	953	996	3	11.5	6
	(G-1c-4)	3.7	—	1775	1979	3	11.5	6
0.8 mph	Apollo	0.0	810	804	—	2	13.5	8
	(021)	3.7	1126	1062	—	2	13.5	8
0.8 mph	Apollo	0.0	—	814	826	2	10.5	5
	(024)	3.7	—	926	944	2	10.5	5
Arm ¹ Exercise	Apollo	0.0	644	649	—	2	13.5	6
	(021)	3.7	723	730	—	2	13.5	6
Switch ² Flipping	Gemini	0.0	425	—	—	5	11.5	11
	(G-1c-4)	3.5	625	—	—	5	11.5	11

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR		Number of Subjects	Vent Flow CFM	Trials
			15 Mins	30 Mins			
Treadmill	Gemini						
1.2 mph	G-1c-4	0.0		824	2	11.5	2
	G-1c-4	3.7		1453	2	11.5	2
2.5 mph	G-1c-4	0.0	1256	1263	1	11.5	1
2.0 mph	G-1c-4	3.7		2079	2	11.5	2

2.0 mph	G-2c-24	0.0	1027		4	11.5	4
2.0 mph	G-2c-24	0.0	1125		4	4.0	4
3.0 mph (6% GD)	G-2c-24	0.0	2309		4	11.5	6
0.8 mph	G-2c-24	3.7	1163		4	11.5	4
0.8 mph	G-2c-24	3.7	1338		2	4.0	2
1.8 mph	G-2c-24	3.7	1929		3	11.5	3

1. The Arm Exercise consisted of lifting an 11.5 lb. weight thru a distance of 18 inches every 5 seconds, alternating between left and right arms.
2. The Switch Flipping task consisted of activating a switch at arms length once every 5 seconds while the subject was sitting in the Gemini mockup couch.

Table 10-22

Caloric Requirements
(After LaChance⁽¹⁴¹⁾)

Activities	Heat production, Btu/hr
Treadmill walking at 0.8 mph: ^a	
Light clothing (normal dress) ---	520
Space suit, unpressurized -----	860
Space suit, pressurized 3.5 psi ---	1520
Space suit, pressurized 5.0 psi ---	2020
Sitting in mockup activating switches: ^b	
Space suit, unpressurized -----	420
Space suit, pressurized 3.5 psi ---	590

^aAt sea level.

^bActivating switch once every 5 seconds at sea level.

A simplified view of the problem, however, is to consider the task as being analogous to carrying weights while walking. As gravity is reduced, the weight carried is consequently reduced, and the energy expended for the task is similarly reduced. An effective method of testing this concept is to reduce traction, on a 6-degree-of-freedom simulator, and to add weights to the subjects to return them to their 1-g weight (267). As the simulated level of gravity is reduced, a pronounced decrease in energy expenditure occurs. When weights are added to the subjects to return them to their original (presimulation) weight, only slight increase in metabolic rate occurs, despite the substantial increments in the total weight being transported. This substantiates the concept that weight reduction is a primary mechanism in producing walking metabolic rates that are lower at reduced gravity than at 1 g. Current studies of elastic fabric or foam-sponge counter-pressure suits may lead to considerable reduction in the energy requirement of extravehicular locomotion (110, 257). The effect of inflated space suits is especially significant in this task. Tables 10-21 and 10-22 and Figures 10-23 and 10-24 indicate locomotion in an inflated suit may more than double the energy requirement over that in an uninflated suit in Earth gravity (123). Figures 10-23, 10-24, and 10-25 represent the sensitivity of metabolic rate of progression to gravitation and to suit pressure.

In general, several forms of 1/6th g simulation give remarkably similar results in predicting energy costs of locomotion (140, 199, 266, 267, 269). These are seen in Figure 10-25a and b. Data are available on combined effect of 1/6th g and pressurized suits as seen in Figures 10-24, 25b, and 26b and c. Preliminary studies of horizontal locomotion in 1/6th g with suit pressurized suggest that in the 2-4 mph range, the energy cost may be equal or less than 50% of that required in the unpressurized condition under 1 g (137, 140, 266, 267). Figures 10-26 b and c emphasize the effect of the different simulators and suits. Figure 10-26c illustrates these data in terms of the lunar weight of the subjects; the metabolic rate is plotted in terms of body

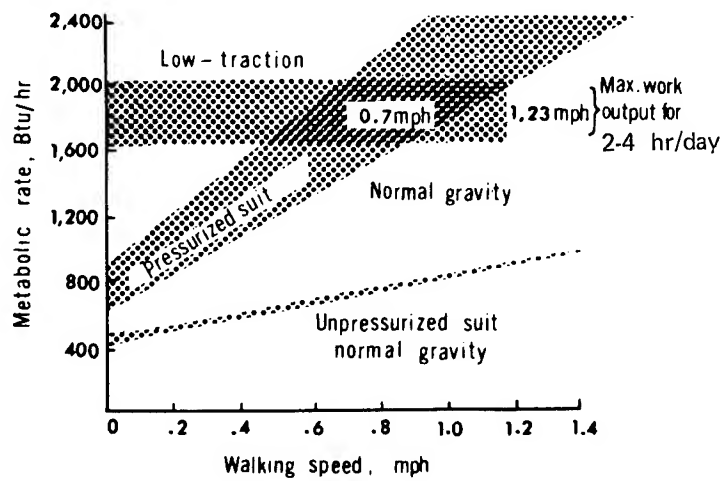


Figure 10-23

Metabolic Cost of Walking in Pressurized Space Suits
Under Normal Earth Gravity

(Modified from Garrett Corp.(3))

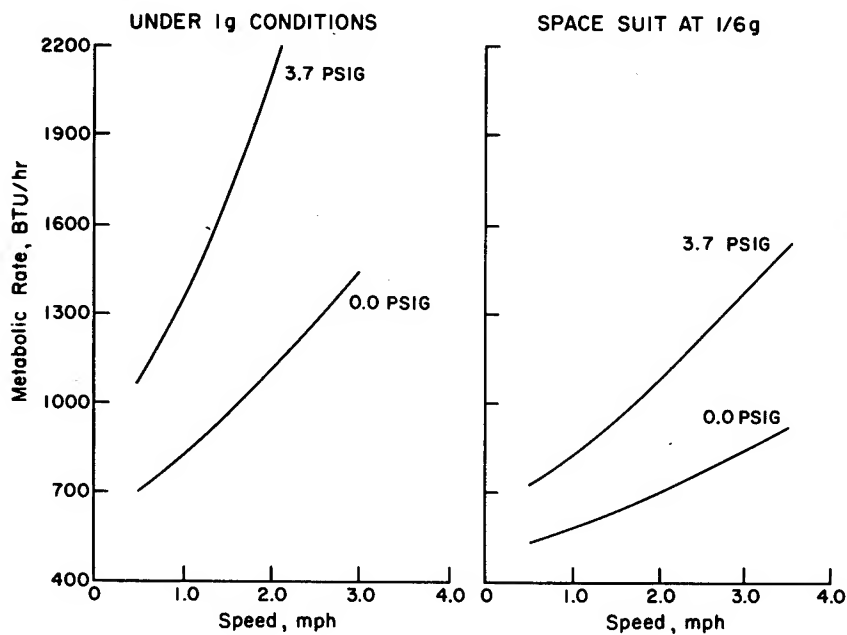


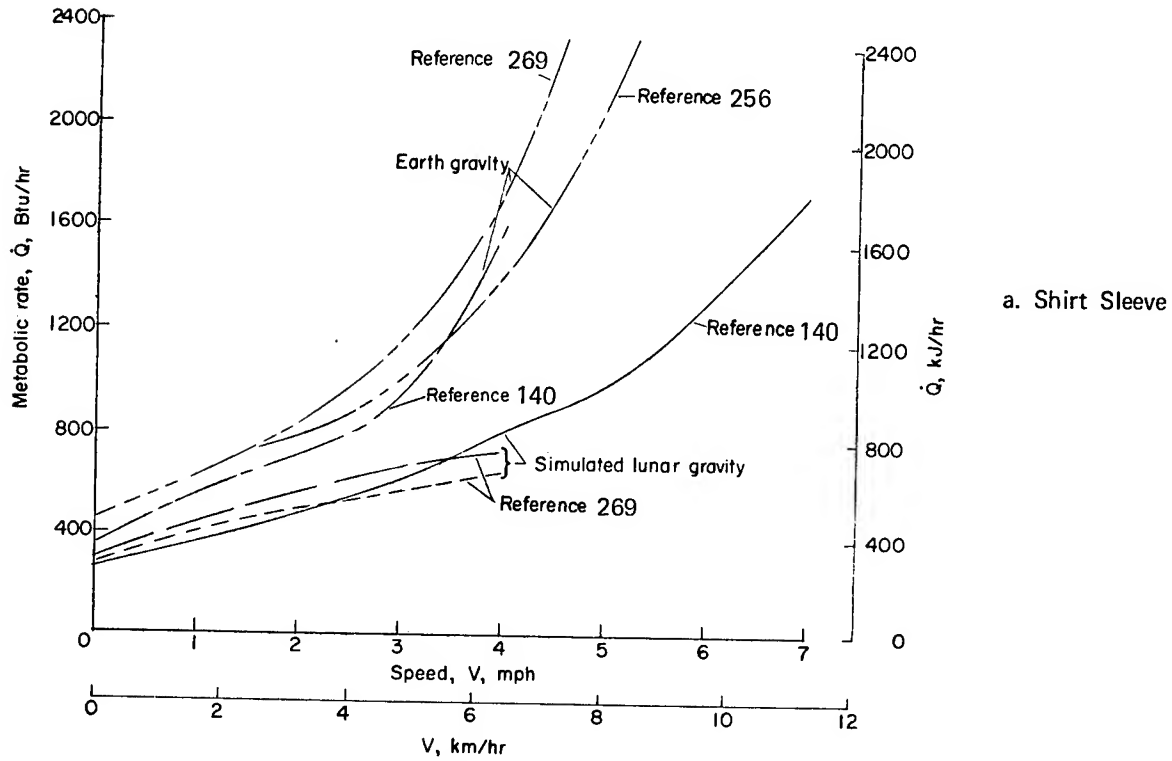
Figure 10-24

Metabolic Rate Comparison

(After Kincaide⁽¹²⁹⁾)

Figure 10-25

Comparative Test Data of Metabolic Cost of Locomotor Work in Subgravity
with Pressurized Suits from Various Sources and for Different Conditions
(After Hewes⁽¹¹³⁾)



b. Pressure Suit

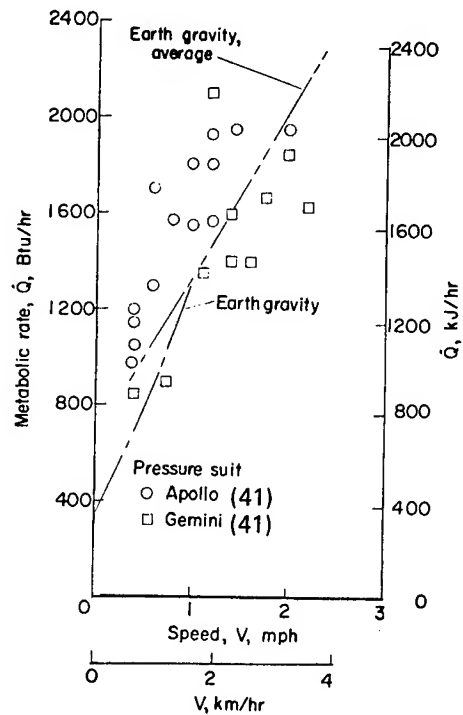
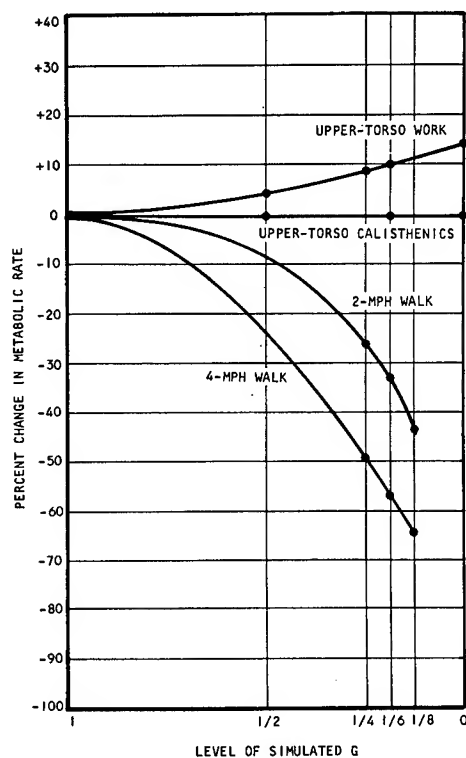


Figure 10-26

Effect of Gravity, Task, Suit, and Simulator Variables on Metabolic Cost of Work



a. (left) Change in Metabolic Rate for Classes of Tasks as a Function of Simulated Reduced Gravity (Shirtsleeves)

(After Wortz⁽²⁶⁷⁾ from data of Wortz and Prescott⁽²⁶⁹⁾ and Prescott and Wortz⁽¹⁹⁹⁾)

b. (bottom) Metabolic Rates for Walking in Different Pressurized Suits on Different Simulators

(After Robertson and Wortz⁽²⁰⁷⁾)

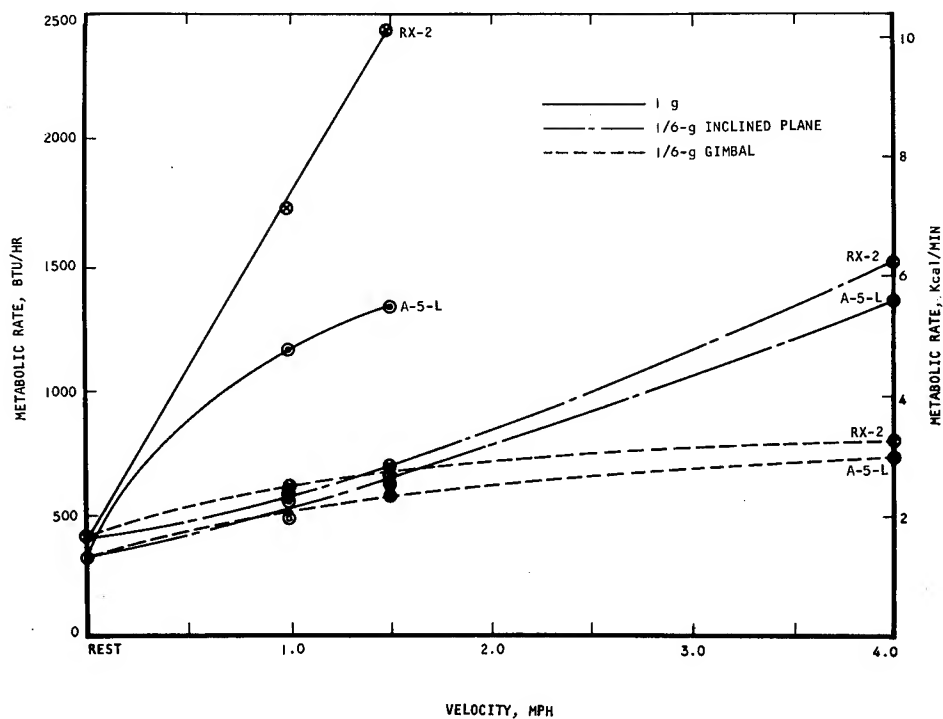
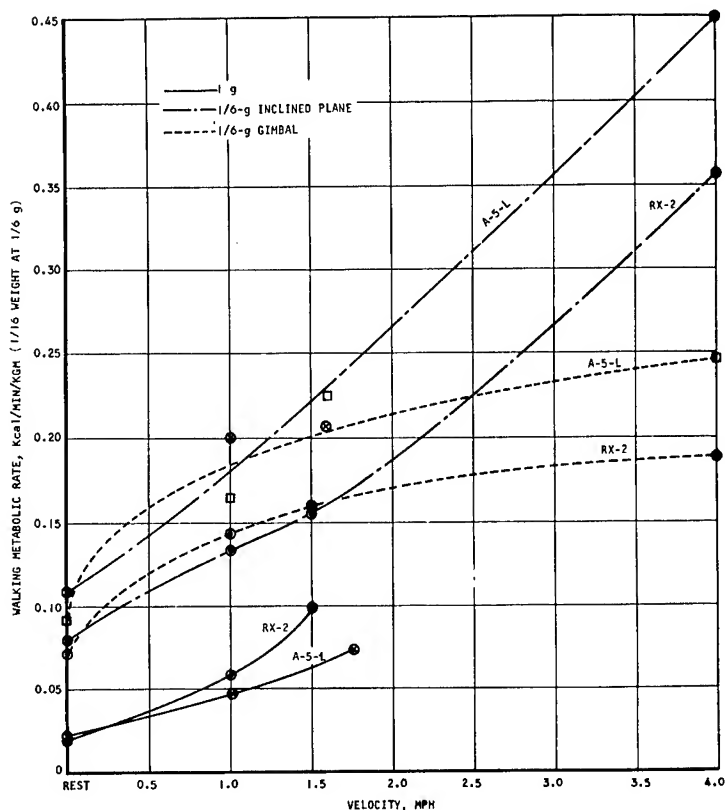


Figure 10-26 (continued)



c. Metabolic Rates for Walking in Pressurized Suits on Different Simulators

Data are normalized for body weights; lunar weight is used for lunar gravity simulated conditions; suits refer to Apollo prototypes.

(After Robertson and Wortz⁽²⁰⁷⁾)

weight for the lunar gravity conditions. The higher cost of walking at 1/6th g (per kg on the lunar surface) indicates a substantial reduction in walking efficiency at 1/6th g. The higher cost (per kgM) for the A-5-L suit over the RX-2 suit indicates an increase in efficiency of work for walking with the heavier hard suit.

These results imply that the bulk and constraints of current pressure suits do not impose as severe penalties on the lunar explorer as has been supposed on the basis of Earth-gravity data. It is possible that this new knowledge will permit greater freedom in making pressure-suit-system trade-offs and selecting the optimum combination of suit features. A preliminary computer program is in preparation for prediction of combined, subgravity, suit-pressurization effects in locomotor tasks (140).

In the 1/6th subgravity, the mode of locomotion is altered by changes in step length, step frequency, and phasic support times (140, 206). Cyclograms of locomotion in pressurized suits on subgravity simulators are available (115, 140). Recent simulator data on non-pressure suited subjects indicate that: (115) the maximum lunar walking and running speeds are about 60 percent of those for earth gravity; for most speeds, the lunar stride was greater and the stepping rate was less than the corresponding Earth values by as much as a factor of 2. The natural or most comfortable gait for the

lunar condition corresponded to a loping gait at about 10 feet per second (3 m/sec) which is much faster than the natural Earth walking gait of about 4.0 feet per second (1.2 m/sec). Sprinting and loping in the lunar conditions produced about the same running speeds, whereas sprinting produced significantly higher speeds in Earth tests. The subjects leaned further forward and swung their legs further forward for lunar gravity tests than for corresponding Earth gravity tests. Furthermore, the subjects tended to walk stiff-legged with very little flexing of the knees for the lunar tests. The theoretical basis for changes in gait and performance are available (56, 162, 211). However, the most "comfortable" lunar gait may not correspond to that requiring the least total expenditure or work. The energy losses incurred as a result of wearing a suit depend on both the rate and amount of flexing the suit. The high loping gait which requires much flexing of the suit and relatively more antigravity work is more costly of oxygen consumption than is a fast walk or run at an equivalent speed (266). More data are required on optimization of lunar gait from an energetic point of view. A compromise between the lope and fast walk or run may prove to be the most practical. More work is needed in this area.

Maximum performance characteristics such as forward velocity, maximum vertical jump height, and broad-jump distance have been attained in inclined plane simulation of 1/6th g as recorded in Table 10-27. (See also Table 7-73.)

Table 10-27

Effect of Subgravity Suit Pressurization on Human
Locomotor Performance of Different Types

(After Hewes⁽¹¹²⁾)

a.	Energy Cost of Locomotion - Unpressurized			
	BTU/hr			
		1/6 g	1 g	Ref.
	2 mph level	560	810	266
	4 mph level	740	1700	
b.		850	1980	266
	4 mph 10° incline	1300	2800	137
	Gravity	Suit pressure psi	Max. forward vel., fps	Vert. jump max. ht., ft
				Broadjump horiz. dist., ft
	1 g	0	11.3	1.7
		3.5	9.2	1.0
	1/6 g	0	5.4	7.7
		3.5	4.0	4.6

Range and Duration on the Lunar Surface

Predictions have been recently made on the maximum work capabilities of distance and range of operations under limitation of fatigue assuming a back pack performance maximum of 2000 BTU/hr for 4 hrs. As was pointed out in the discussion of Figure 10-15, exercise of 2000 BTU/hr for 4 hrs is probably beyond the capabilities of most of the astronaut group. The back pack, therefore, has excess capacity built into it for emergency purposes. The weakest link in these predictions is the lack of adequate oxygen consumption data on pressurized subjects with back packs at 1/6th g. The range-penalty predictions incurred by wearing the pressure suit and back pack are illustrated in Figure 10-28. This shows the range reduction, in terms of percentage of shirtsleeve range, for various speeds under both lunar and Earth conditions. The restrictions of the pressure suit system on range capability were shown to be appreciably affected by both gravity and locomotive speed. The general effects of increased speed are a decrease in range penalties for lunar gravity and an increase for Earth gravity. These effects are attributed to the changes in gait characteristics (stride and stepping rate) required to produce the speed changes for the two different gravity conditions.

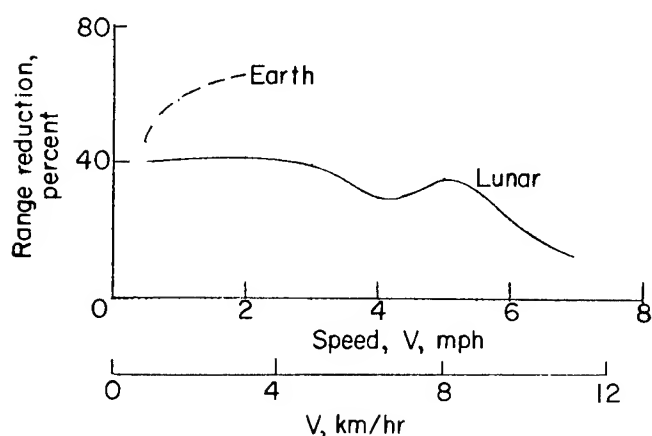


Figure 10-28

Estimated Combined Effect of Pressure-Suit-System Bulk and Stiffness on the Maximum Range of Lunar Explorers

(After Hewes⁽¹¹³⁾)

Assuming no rest periods or optimization of work-rest cycles, range predictions can be made from the data of Figures 10-25, 10-28 and 10-15 (lower curve) under different locomotion rates and duration of activity. Figure 10-29 shows these predictions under Earth and lunar conditions for heat dissipation and fatigue limits. The straight lines radiating from the origin of Figure 10-29a correspond to constant rates of energy expenditure and are identified by the corresponding fatigue limits. The intersection (indicated by the symbol) of each line with the experimentally derived range-factor curves corresponds to the maximum speed which can be sustained for a specific period of time without exceeding the assumed fatigue limits.

The maximum range attainable for a given speed without consideration of other factors except total life-support-system capacity is determined by multiplying the range-factor value in Figure 10-29a by the value for the system capacity (assumed to be 4800 BTU or 5070 kJ for this analysis) and dividing by 1000. The maximum range for all speeds is shown in Figure 10-29b

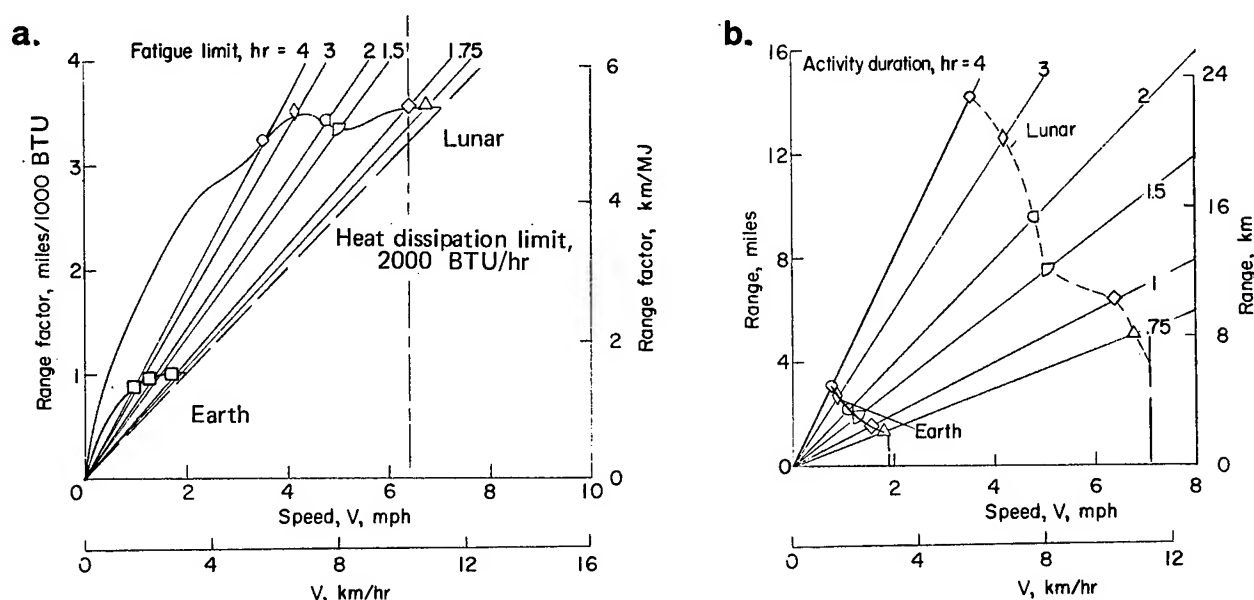


Figure 10-29

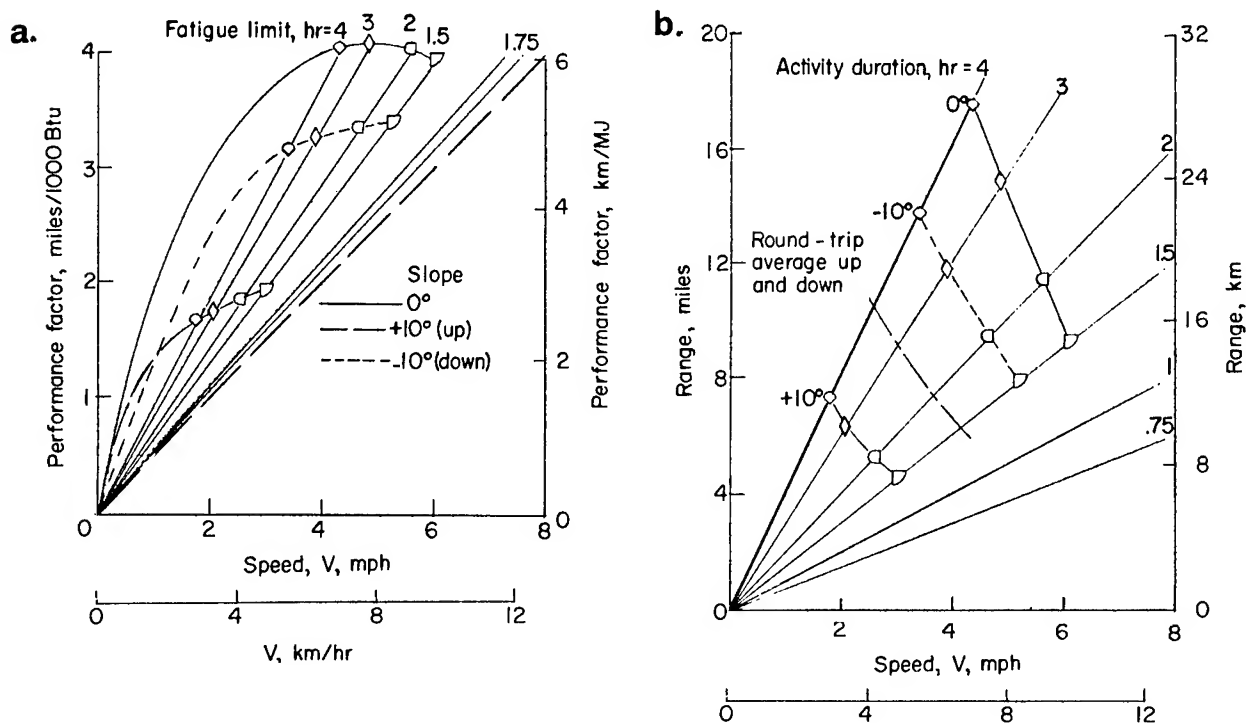
Estimated Effects of Speed, Activity Duration, Fatigue, and Suit System Limits on Range Capability of Lunar Explorers on Lunar Surface and Earth

(After Hewes⁽¹¹³⁾)

by the solid curves which appear similar to the curves in Figure 10-29a. The maximum range attainable for a given speed, if only the duration of the mission is considered, is defined in Figure 10-29b by the straight lines radiating from the origin and designated by the specific values of activity duration ranging from 0.75 to 4 hours. The heavy straight line corresponding to a 4-hour period represents the maximum range as limited by the assumed maximum mission-duration limit. The effect of the assumed fatigue limits on the maximum range attainable for a given period of activity is determined by graphically projecting the various intersection points in Figure 10-29a to the corresponding activity duration lines in Figure 10-29b.

The resulting intersections in Figure 10-29b, denoted by symbols, are connected by the short-dash line which represent the fatigue boundary. The vertical lines in Figure 10-29b and heavy dashed line in Figure 10-29a represent the loci at which the metabolic rate reaches the maximum heat dissipation capacity of the life support system at 2000 BTU/hr.

Review of the limited reference data and study of one subject walking up and down slopes in $1/6g$, suggest that activity on a 10° sloping surface, whether ascending or descending, reduces the range capability with the effect of ascending being about three times that of descending (113, 139). Inasmuch as a complete round trip over sloping terrain will usually result in the same uphill distance as downhill distance traversed, the effects of the slope can be averaged together to give a more realistic indication for operating over uneven terrain. The average curves given in Figure 10-30 show that the range capability of 10° sloping surfaces is about half of that for a level surface. The curves are read in the same manner as Figure 10-29.



Curves are based on data from one subject(139)

Figure 10-30

Estimated Effect of Surface-Slope Variations on the Range Capability of Lunar Explorers

(After Hewes⁽¹¹³⁾)

In using the data of Figures 10-29 and 10-30, it must be remembered that the curves are extrapolations from several limited simulation studies. In the same simulator, energy consumption predictions vary $\pm 15\%$ (139). When the uncertainties of fatigue limits of the astronaut group are considered (Figure 10-15), the range estimations must be taken with a wide range of expected error (113). Optimization of work-rest cycle for maximum range remains to be accomplished.

A new back pack for lunar operations is under development (233).

Energy Requirements for Apollo

General thermodynamic requirements anticipated for the several phases of the Apollo mission are shown on Figure 15-5 of Water, (No. 15) (25). In addition to these general standards, Table 10-31 represents specific recommendations for different aspects of the orbital flight.

The hourly breakdown of metabolic activity anticipated for the orbital phase of the Apollo mission is seen in Table 10-32a and b. Hourly metabolic requirements for the LEM and lunar surface operational phases of the mission are seen in Figure 15-5 of Water, (No. 15). The post-landing requirements are related to wave height and thermal conditions as seen in Table 10-32c.

Table 10-31
Metabolic Requirements With
Spacecraft Cabins in Orbit
(After Vinograd⁽²⁵⁵⁾)

Hourly Partition of Metabolic Rate Anticipated for the Orbital Phases of the Apollo Mission
These data are on the conservative side for safety purposes.
(After Billingham⁽²⁵⁾)

	Time Hours	Metabolic kcal/m ² hr	Heat Output kcal	BTU
Sleep	8	40	640	2,540
Off-duty	7	50	700	2,780
On-duty (suited)	8	65	1,040	4,130
Exercise	1	200	400	1,580
TOTAL	24		2,780	11,030

A prolonged period of decompression is assumed and the work-rest cycle altered as follows:

c. Post-Landing Metabolic Requirements

* Allowable Effective Temperature 600 BTU/hr. heat load - 86.5F
400 BTU/hr. heat load - 88F

10-41

Storage Penalties for Oxygen Systems

Weight and volume storage penalties for gaseous and cryogenic oxygen (215) are covered with other gases in the Inert Gas Environment, pages 11-20 to 11-27 and Figures and Tables 11-10 and 11-12. Since penalties for solid chemical storage are closely tied to water production, R. Q., and other factors, they will be discussed here.

Because relatively stable forms of chemical compounds containing a high percentage of oxygen and nitrogen are available, this mode of storage appears particularly suitable for cabin pressurization, erection of inflatable structures, emergency breathing supplies, spacesuit backpacks, and nitrogen supplies for missions requiring small units with long standby time prior to operation. Several excellent reviews of the subject are available (32, 33, 53, 155, 165, 180, 190, 193, 194, 215).

Oxygen producing chemicals can be divided into four major groups: (1) Alkali and alkaline earth peroxides, superoxides, and ozonides, (2) alkali and alkaline earth chlorates and perchlorates, (3) hydrogen peroxide, and (4) water electrolysis.

Table 10-33 shows some of the pertinent physico-chemical properties of oxygen-producing chemicals suitable for space cabin use. Lithium peroxide is not available commercially, and calcium superoxide, because of its low yield per pound in commercially available material (50 percent impurity), is of value only in extravehicular suit backpacks where its resistance to fusion is of merit.

Potassium and sodium peroxides are compounds of primary interest in the first category. They absorb water and carbon dioxide and produce carbonates, bicarbonates, and oxygen. In terms of oxygen storage capacity, the ozonides are superior to corresponding superoxides (see Table 10-33). The potassium and sodium ozonides are readily prepared (194). As with the superoxides, lithium ozonide theoretically has the most desirable characteristics

Table 10-33
Comparison of Oxygen-Producing Chemicals
(After Coe et al⁽⁵³⁾ and Petrocelli⁽¹⁹²⁾)

	KO ₂	NaO ₂	Li ₂ O ₂	NaO ₃	LiNO ₃	LiClO ₄	NaClO ₃	H ₂ O ₂	H ₂ O ₂
Available O ₂ (theoretical), weight percent.....	33.8	43.6	34.8	56.3	23.2	60.1	45.1	47.1	47.1
Purity.....		0.90	(*)		1.00	1.00		0.90	0.98
Available O ₂ , lb/lb.....	0.32	0.392	0.375	0.56	0.232	0.601	0.40	0.423	0.461
Density, lb/in. ³	0.0237		0.0774		0.0861	0.0878	0.0815	0.0502	0.0515
Heat of reaction, Btu/lb ^b	^c 415	^d 635	^e -363	+1515	-488	-596	+422	+1106	1214
H ₂ O balance, lb/lb.....	-0.0207	-0.0246		-0.136	0	0	0	+0.577	+0.539
H ₂ O balance, lb/lb O ₂	-0.0862	-0.0862		-0.225	0	0	0	+1.34	+1.17
CO ₂ balance lb/lb.....	0.31	0.40	0.96	0.31					

* 10 percent Li₂O₄.

^b + Indicates exothermic reaction; - indicates endothermic reaction.

^c 2 KO₂ + 1.23 CO₂ + 0.23 H₂O = 0.77 K₂CO₃ + 0.46 KHCO₃ + 1.5 O₂.

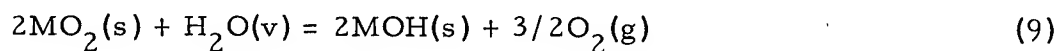
^d 2 NaO₂ + 1.23 CO₂ + 0.23 H₂O = 0.77 Na₂CO₃ + 0.46 NaHCO₃ + 1.5 O₂.

^e Li₂O₂.

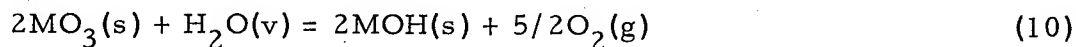
in terms of oxygen availability (0.73 lb/lb of compound), but all attempts at synthesis have failed (194). Lithium peroxide has been synthesized. Chlorate candles are stable materials which can be burned in generators to produce oxygen at a constant rate. Hydrogen peroxide is a strongly oxidizing liquid which can be decomposed catalytically to generate oxygen, water vapor, and heat.

Superoxides, Ozonides, and Peroxides

The reactions of superoxides with water vapor and carbon dioxide to form oxygen have been reviewed, and much of the following discussion is based on this study (192). These reactions can be expressed by the following equations:

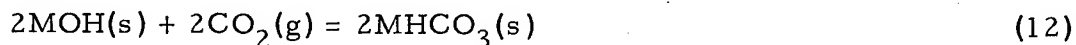
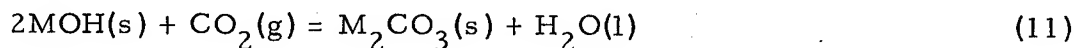


and



where s = solid, v = vapor, g = gas, l = liquid, M = alkali earth element.

In turn, carbon dioxide is removed from the breathing atmosphere through reactions with the product hydroxide which cause the formation of carbonates and bicarbonates:

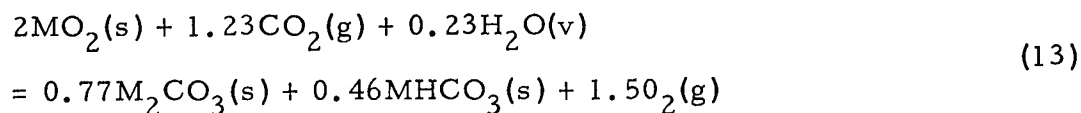


On the basis of these stoichiometries, the theoretical respiratory quotient (RQ), capable of being obtained with superoxide systems, ranges from 0.67 (carbonate formation only) to 1.33 (bicarbonate formation only). With ozonide systems, the theoretical RQ range is 0.40 to 0.80 for the corresponding stoichiometries.

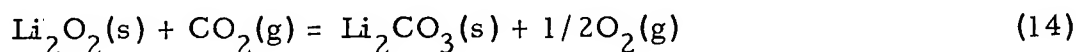
The early concern about RQ mismatch with humans has been resolved by analysis of alternate reaction mechanisms. At first, superoxides were evaluated on the basis of a stoichiometry which involved the formation of the metal carbonate only (Equation 11). Thus, the RQ of the system was expected to be 0.67 and oxygen overproduction was predicted. The other factor which contributed to doubts about the superoxides is based on the experience gained from the use of potassium superoxide canisters in self-contained breathing apparatus for firefighting and mine rescue. Such canisters resulted in very inefficient utilization (about 80 percent) of the superoxide charge. The inefficiency of such canisters can be attributed to the formation of a hard crust of potassium hydroxide on the reaction surface of the superoxide, thereby preventing water vapor in the exhaled breath from contacting the unreacted superoxide. The discovery that bicarbonate does form under certain conditions of temperature and relative humidity has shown that the problem of oxygen overproduction, anticipated when only carbonates were thought to be formed, is insignificant. Semipassive superoxide systems have been designed

to incorporate control of flow rates and relative humidity to achieve better than 90-percent oxygen recovery from the superoxide supply (127, 128, 166).

In effect, the following stoichiometry can be achieved in a properly designed superoxide reactor.

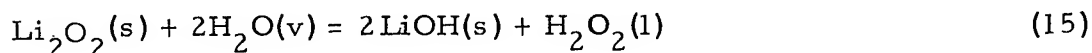


Lithium peroxide (Li_2O_2) is of interest as an air vitalization material because in the presence of moisture it can be caused to react directly with carbon dioxide to yield oxygen and lithium carbonate: (165, 180)

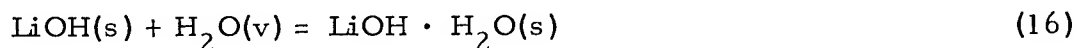


Thus, it is possible to remove 0.96 pound of carbon dioxide with each pound of lithium peroxide from a closed breathing system and, at the same time, to return 0.35 pound of oxygen to the system. The RQ for a system employing only lithium peroxide would be 2.0. As a result, the use of this chemical would require an additional source of oxygen. The theoretical capacity of lithium peroxide for carbon dioxide is about 4 percent greater than the capacity of lithium hydroxide for carbon dioxide.

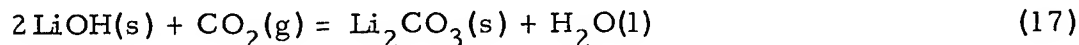
In the presence of water vapor, carbon dioxide absorption and oxygen evolution by lithium peroxide does occur, but oxygen generation lags far behind the amount anticipated on the basis of Equation (14) (165, 180). However, the absorption of carbon dioxide and the evolution of oxygen proceed by two different reactions; lithium peroxide and water vapor first reacting to yield the active carbon dioxide absorbents, LiOH , $\text{LiOH} \cdot \text{H}_2\text{O}$, and hydrogen peroxide:



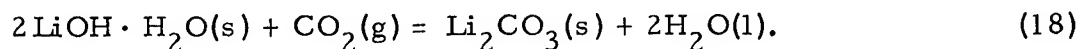
and



Carbon dioxide is then absorbed via:



and



Oxygen is evolved as a result of the decomposition of the H_2O_2 :



It has been shown that in order to achieve theoretical yields of oxygen, it will be necessary to develop a catalyst to insure the decomposition of all the H_2O_2 formed in Equation 15 (165).

The chemistry of lithium peroxide has been reviewed (63). Preliminary respiratory exchange of this compound has been studied (70). The state of the art of lithium peroxide, as an air revitalization material, is not nearly as advanced as it is for superoxides. Continued basic research is necessary in order to optimize lithium peroxide as a carbon-dioxide absorber and oxygen source.

Lithium superoxide (LiO_2) if it exists in a stable form would be of great value for air regeneration. Lithium superoxide potentially represents the lightest alkali metal oxide in terms of weight of agent per weight of oxygen produced. Experimental efforts to produce this compound have given ambiguous results. An effort has been made to estimate the thermodynamic properties of this compound, to determine whether further experimental efforts are worthwhile, to predict suitable experimental conditions, and to draw conclusions about the stability of the compound (240). Unfortunately the results of this study offer little encouragement for the availability of this material. Consideration of the free energies of various decomposition reactions showed that the tendency to decompose corresponds to 15 kcal from 100° to 300° K. This tendency is so much greater than the uncertainty of the estimates that lithium superoxide can be considered unstable at all temperatures. Furthermore, none of the usual methods of promoting stability are sufficiently effective to overcome this instability. Substances can be stabilized by putting them into solid solution. For example, phase data have shown the existence of solutions of sodium superoxide in sodium peroxide. It has been shown that, theoretically, no significant concentration of lithium superoxide can be stabilized in this way (240). This conclusion might be different if a mixed compound that has a definite heat and free energy of formation is formed. Such compounds do not usually have sufficient free energy to overcome the instability of lithium superoxide. Further attempts to prepare lithium superoxide do not appear promising. Even if the compound were prepared, it would tend to decompose spontaneously. It would probably not be safe to carry such an unstable compound in a manned space cabin.

Design equations as well as weight and power tradeoffs for the use of superoxide canisters in spacecraft have been reviewed (53, 215, 217). In any tradeoff study, a comparison must ultimately be made between the equivalent weight of carbon dioxide absorption by superoxide and LiOH with water and oxygen creditation. Weight of the potassium subsystem is considerably greater than the sodium (215). The total subsystem equivalent weight is the total of the sodium superoxide consumption, the canister weight, accessory weight, power-loss penalty, heat-rejection penalty, and material balances weight. When a deficit of water exists, the material balance requires additional water and causes a penalty. However, weight (lbs) of oxygen which is added by the system can be subtracted from the consumption weight by a factor of $W_{\text{O}_2} = 2.28 N_\tau$, where N is the astronaut crew size and τ is the time in days. The system equivalent weight penalty is:

$$W_e = (W_{\text{NaO}_2} - W_{\text{O}_2} + W_{\text{H}_2\text{O}}) + W_{\text{can}} + W_{\text{acc}} + W_P + W_Q \quad (20)$$

$$W_e = (5.52 - 2.28 + 0.185) N\tau + 3.423 N^{2/3} + (5.2 + 1.79\sqrt{N}) + [(PL)_t(PP)] + 1.70N(RP) \quad (21)$$

where W = weight, can = canister, acc = accessories, P = power equivalent, Q = heat equivalent, e = system equivalent, τ = time in days, (PL) = power loss in watts, (PP) = vehicle weight penalty for power, R = gas constant, and t = total number.

The use of lithium chlorate candles does not appear to be competitive with that of the superoxides on a weight basis alone (215). Hydrogen peroxide as a source of breathing oxygen does also not appear favorable. The use of electrolytic systems, however, appears favorable when closed-loop systems of water salvage are considered (53, 215, 217). System integration with other processes is the determining factor in weight tradeoffs of this system.

PHYSIOLOGY OF THE OXYGEN AND CARBON DIOXIDE PARTIAL PRESSURE ENVIRONMENT

Evaluation of physiological response and performance in an altered oxygen and carbon dioxide environment requires an understanding of the distribution and role of these gases in the body.

Oxygen and Carbon Dioxide in the Lung

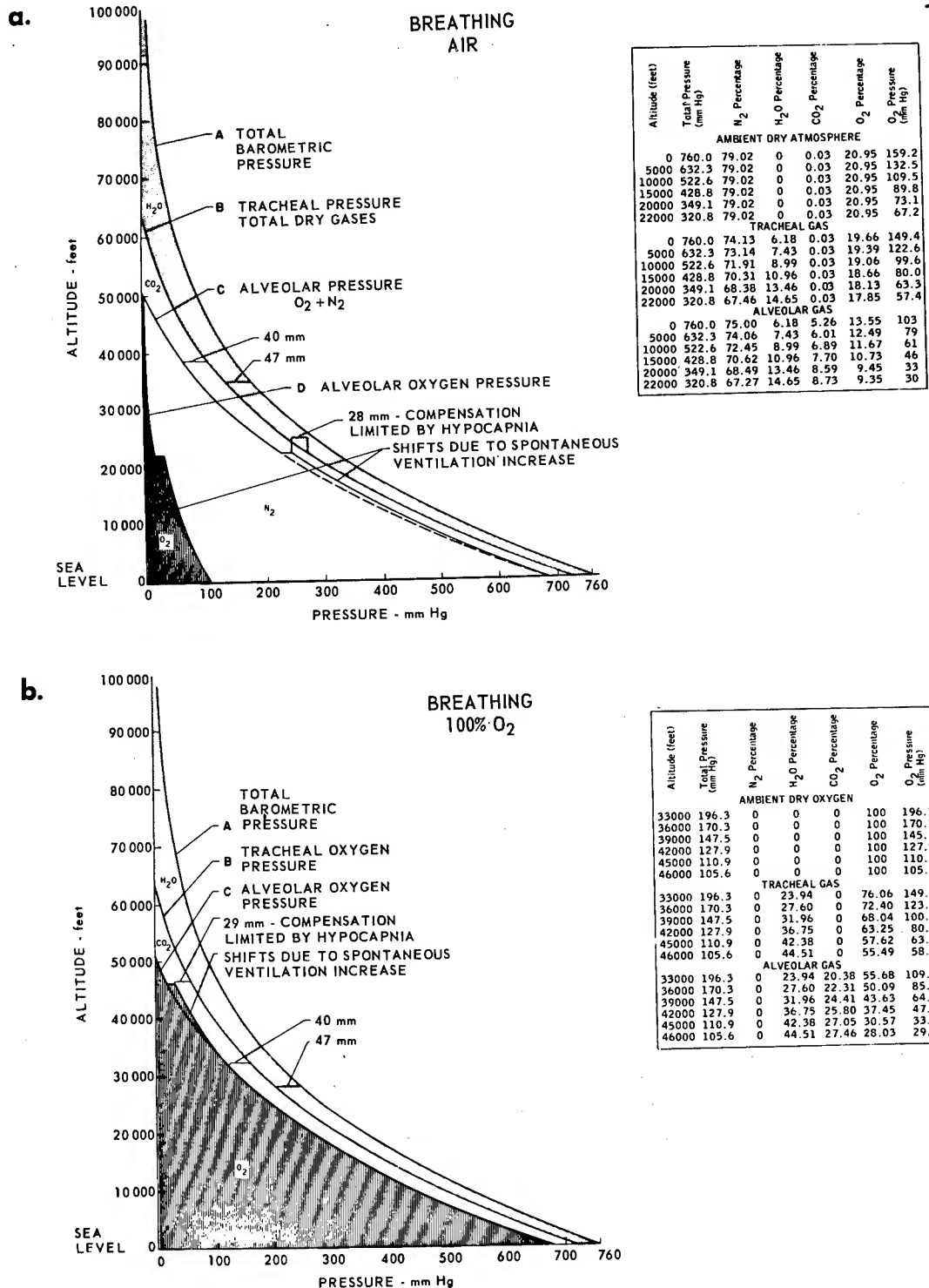
Figure 10-34 summarizes the key physiological interaction between the atmosphere and the lung-body system by comparing the composition (partial pressure) of tracheal and alveolar gases at different altitudes in subjects breathing (a) air, and (b) 100% oxygen. In both cases, inspired gases pick up water from the wet respiratory passages until the partial pressure of water vapor reaches saturation pressure of 47 mm Hg at body temperature (98.6°F or 37°C). Thus, the total pressure of dry gases in the trachea is always 47 mm less than the total barometric pressure (curves A and B), the tracheal oxygen and nitrogen pressures always being 9.9 mm Hg and 37.1 mm Hg, respectively, less than their dry air ambient pressures.

As inspired gases pass into the lungs they mix with residual air in the alveoli, lose oxygen to the blood and pick up carbon dioxide released by the blood. The carbon dioxide mixes with the alveolar gases to an equilibrium partial pressure of 40 mm Hg. The total partial pressure of oxygen and nitrogen in the lungs (alveolar gas, curve C) is therefore 40 mm less than that in the tracheal gas. In most subjects the body compensates automatically (within a limited range) for low oxygen pressure by increasing the breathing rate and/or depth (ventilation) until the point where hypocapnia (too low carbon dioxide concentration) sets in. This increases the partial pressure of oxygen (P_{O_2}), within the compensatory range, as shown on curve D. This response sets the average "ceiling" at 24,000 ft instead of 17,000 ft where it would be without increase in ventilation. The abrupt cessation of the hyperventilation effect at 23,000 feet in graph 10-34a and at 45,000 feet in graph 10-34b represents lack of sufficient experimental points.

Figure 10-34

Partition of Gases in Trachea and Alveoli at Different Barometric Pressures

(After Roth and Billings⁽²¹⁶⁾, adapted from Hanff and Pegues⁽¹⁰⁶⁾)



In the few cases studied at 50,000 feet, even the non-acclimatized subject hyperventilates and lowers his PA_{CO_2} to 20-25 mm Hg, though not sufficiently to maintain a PA_{O_2} of 30 mm Hg critical for consciousness (13). The well acclimatized subject may maintain a sufficiently high PA_{O_2} to remain conscious "indefinitely," with PA_{CO_2} in the neighborhood of 12-15 mm Hg. Above 52,000 feet altitude, whether on air or 100% oxygen, the alveoli contain only water and carbon dioxide. Enriching the inspired air with supplementary oxygen will move curve D toward the right, as nitrogen is replaced with oxygen. The more oxygen is added, the farther to the right the curve shifts, until at 100% oxygen it becomes the same as curve C except for the portion shifted by the spontaneous increase in ventilation.

The physiological relations between the total pressure of the atmosphere and the % oxygen required for normal function has been reviewed in Figure 12-1 of Pressure, (No. 12). Nomograms and charts relating different pressures and partial pressures of oxygen and other constituents to equivalent alveolar P_{O_2} 's are available (157). One must consider the effects of both hypoxia and hyperoxia.

Hypoxia

The space environment and planetary atmospheres appear to be lacking in adequate oxygen (134, 174, 175, 184). Hypoxia is therefore a constant problem. Unfortunately, except for some oxygen stored in the myoglobin of "red muscle," the only oxygen stored by the body is that actually being transported by the blood stream. Muscles can function temporarily without oxygen, but in the process build up toxic fatigue products that limit their activity. The tissues most sensitive to oxygen deficiency, such as the central nervous system (brain and eyes) cannot function without oxygen. The capacity for anaerobic work appears to be preferentially restricted to the white muscle fibers, while the red fiber depends more on aerobic metabolism. The heart consists entirely of red muscle tissue and is, therefore, nearly as sensitive to oxygen lack as the central nervous system.

The brain in man is only 2% of the body weight but has about 20% of the total body oxygen consumption. As arterial oxygen tension falls, progressive impairment occurs in the central nervous system, as indicated in Figure 10-35 by zones of increasing density. These changes occur in resting men who are not fatigued or otherwise stressed. The oxygen saturation of arterial blood for resting men is also shown as a function of oxygen tension (the hemoglobin dissociation curve). A range of saturations for each value of tension is shown, because temperature and pH influence the saturation values. Individual variability and time dependency are characteristic of these data. The minimum and average duration of effective consciousness in human subjects following rapid decompression breathing air and oxygen are seen in Figure 12-12 of Pressure, (No. 12). Above 20,000 to 23,000 feet, unacclimatized subjects breathing air will lose consciousness after a variable period of time. Individual susceptibility varies widely except at the highest altitudes.

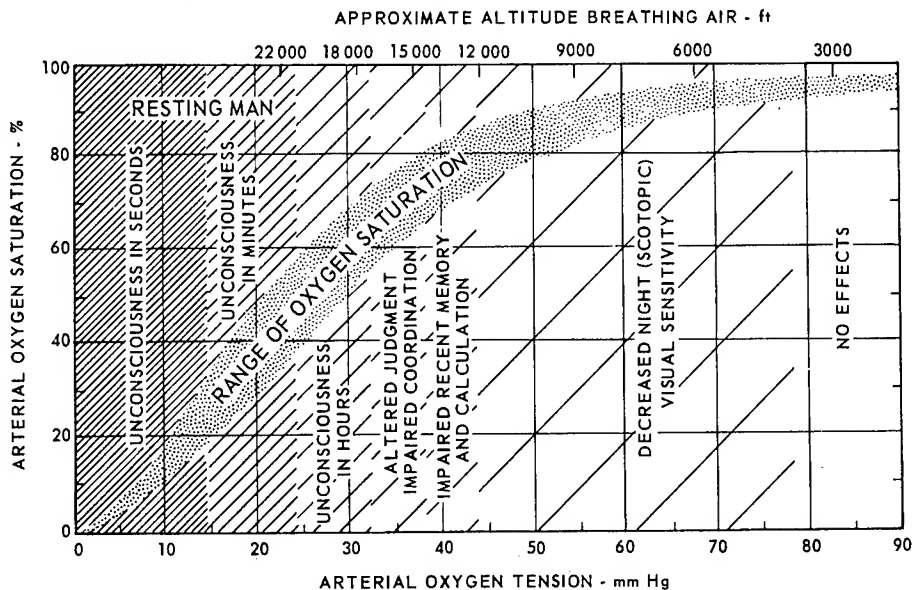


Figure 10-35

General Effect of Hypoxia on Arterial Saturation and Body Function

The ambient tracheal and alveolar pressure of oxygen corresponding to the altitudes and arterial oxygen tensions of this figure may be obtained from Figure 10-34.

(After Billings and Roth⁽²⁶⁾, adapted from USAF Flight Surgeon's Manual⁽²⁴⁸⁾, McFarland⁽¹⁵²⁾, and Boothby, (ed.)⁽³¹⁾)

The time required to reach hypoxic threshold after decompression of cabins of different atmospheric composition can be determined from Figures 12-1 and 12-9 of Pressure, (No. 12) and Figures 10-34 and 10-35.

The visual functions appear most sensitive to hypoxia. Figure 10-36 summarizes some of the thresholds of visual determination. A semi-quantitative review of visual performance after different degrees of hypoxia is seen in Figures 10-37 to 10-39. Sustained acceleration along the G_x axis will cause arterial unsaturation and produce similar decrement in performance. This relationship is noted for G_x in these figures. The degradation of vision by acceleration is covered in Acceleration, (No. 7).

Figure 10-37 represents the change in central brightness contrast discrimination at different arterial oxygen saturations and G_x values. The data can be used to evaluate human capability in detection tasks at luminance levels near threshold. (See Light, No. 2.)

Figure 10-38a summarizes visual performance decrements for dark adaptation, central brightness, contrast, central field extent and central acuity. The dashed portion of the curves are speculated.

Figure 10-38b compares the contrast sensitivity curves of Figures 10-37 and 10-38a. Difference in effect between P_{O_2} and $+G_x$ may be seen to be roughly constant at about 10-12% impairment. While this is a sizeable difference, it can be expected that differences in effect on non-sensory tasks

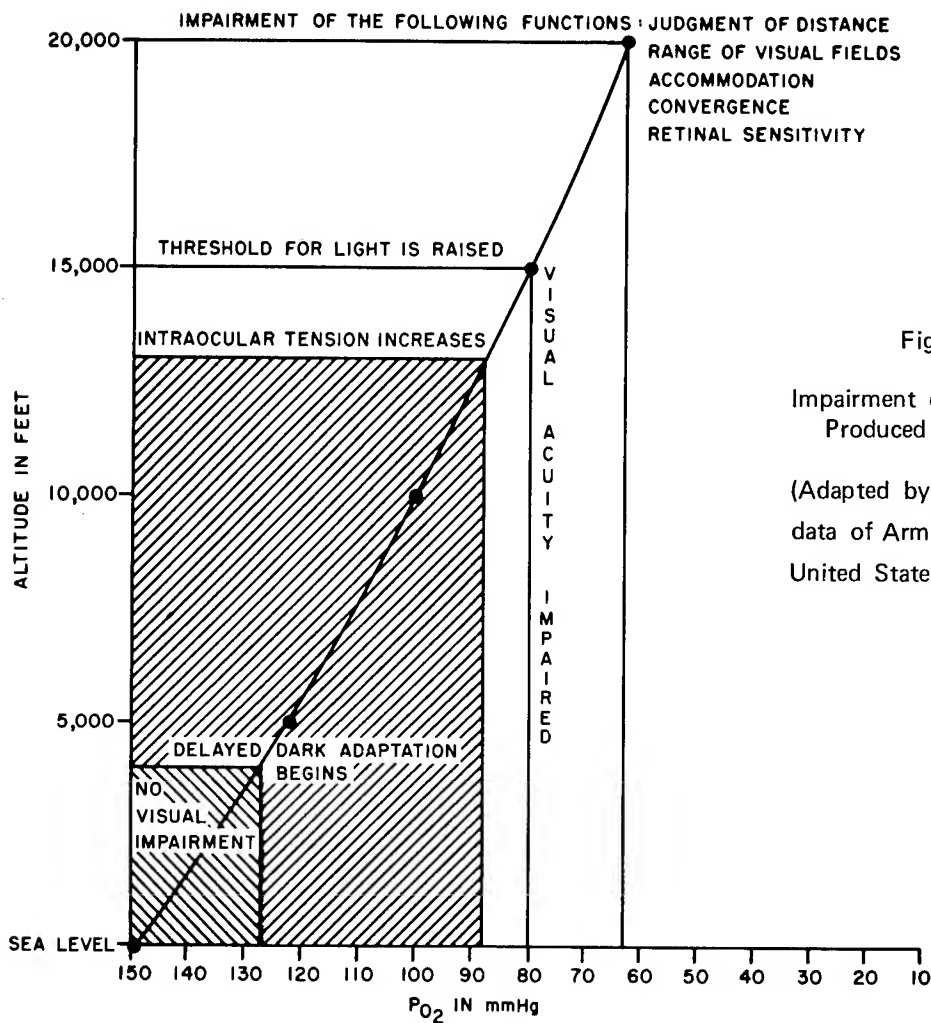


Figure 10-36

Impairment of Visual Functions
Produced by Hypoxia

(Adapted by Finkelstein⁽⁸²⁾ from
data of Armstrong⁽⁶⁾ and the
United States Air Force⁽²⁴⁹⁾)

Figure 10-37

Brightness Contrast Discrimination at Given
Arterial Oxygen-Saturation Level or G_x Level

Data from exposures of 90 seconds at peak G.

(From the data of Chambers⁽⁴⁷⁾ and Alexander⁽⁴⁾)

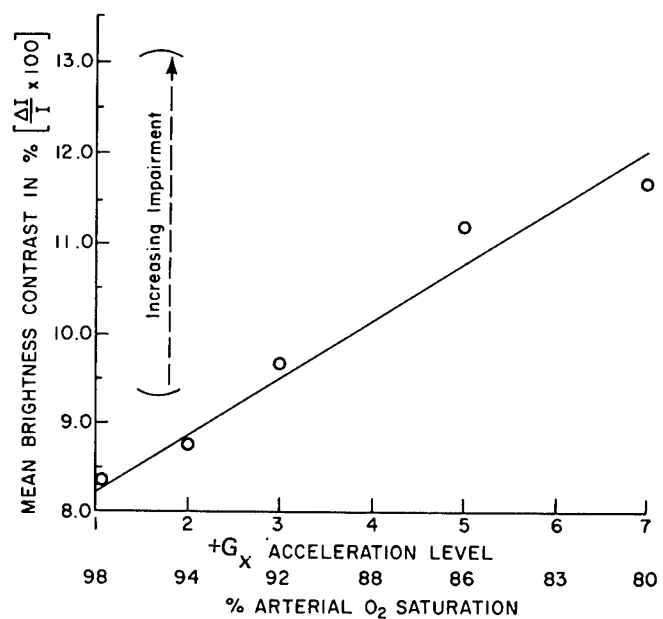
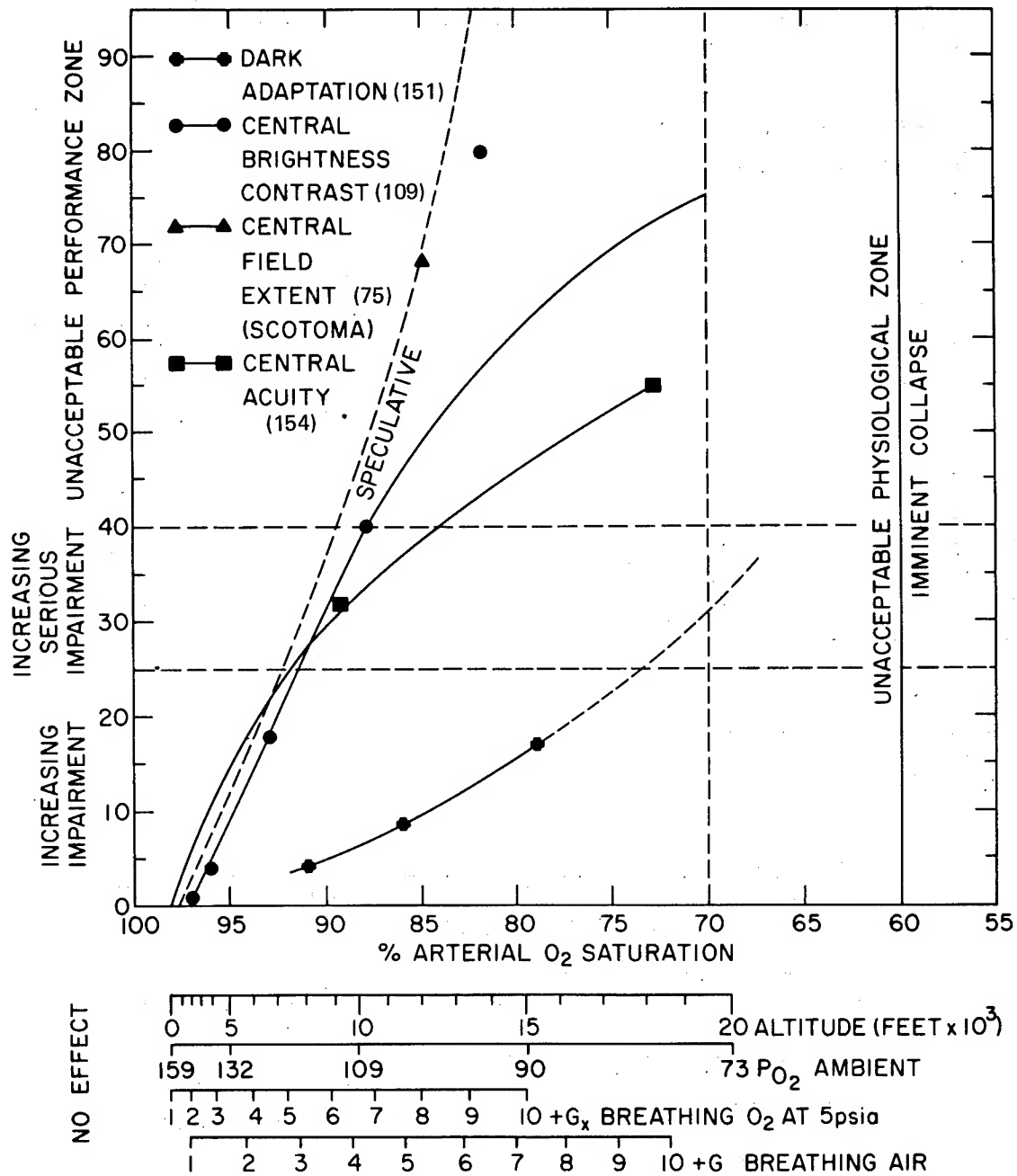


Figure 10-38

Effects of Hypoxemia and G_x Acceleration on Visual Performance

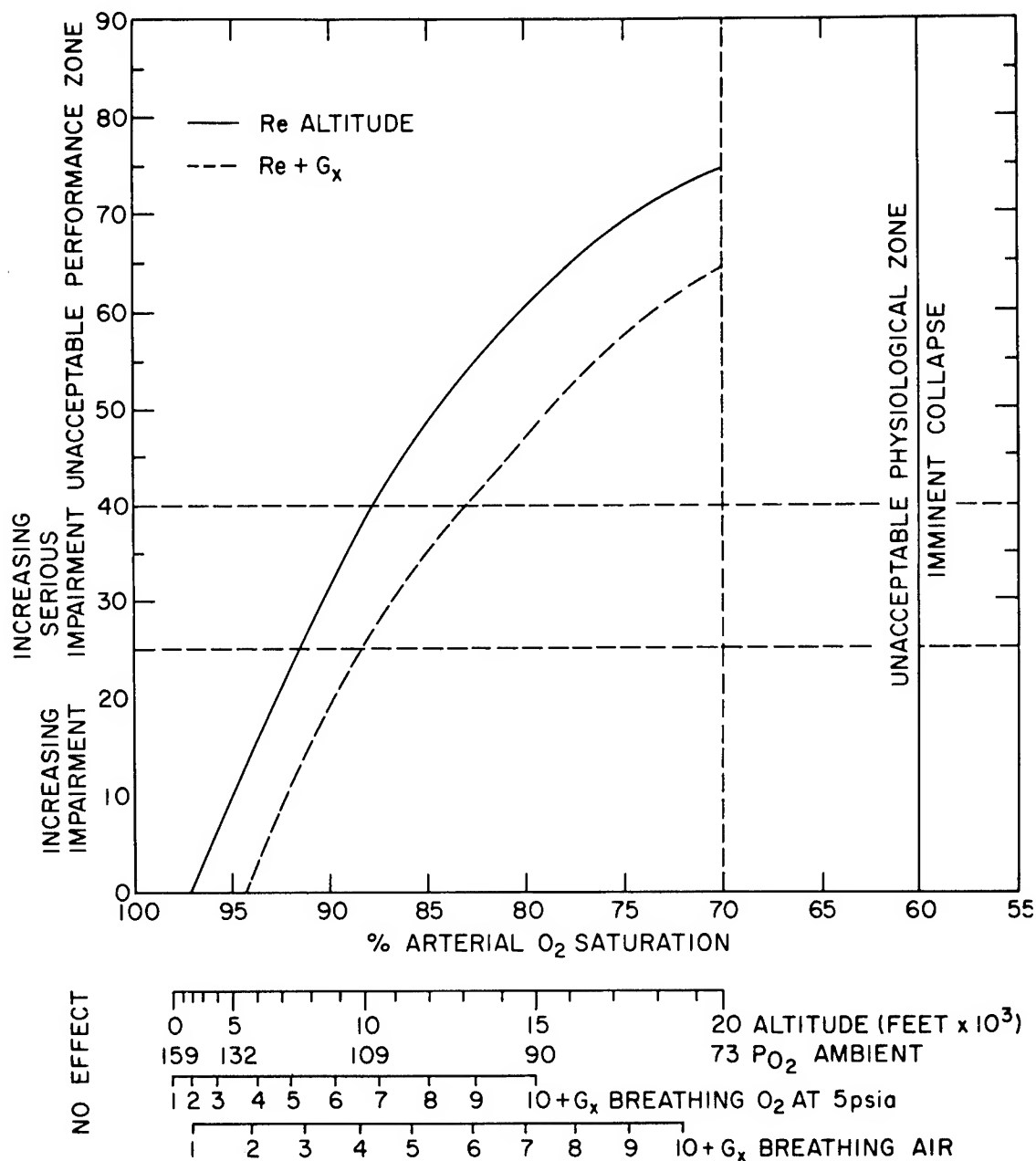
a. Response of Several Visual Functions to Hypoxemia



(Adapted by Teichner and McFarland⁽²⁴⁶⁾ from the given sources)

Figure 10-38 (continued)

b. A Comparison of Visual Contrast Sensitivity Decrements Induced by Reduced Partial Pressure of Oxygen and Those Induced by Acceleration



(After Teichner and McFarland⁽²⁴⁶⁾, adapted from Chambers⁽⁴⁷⁾ and Hecht et al⁽¹⁰⁹⁾)

would be considerably smaller. The closeness of the two curves is remarkable in view of the number and extent of data-leaps that were made. These upper limits of $+G_x$ arrived at by extrapolating from altitude-derived, blood oxygen curves are not too unreasonable in terms of the performance data that have been reported (46, 88). These data apply only to problems of low (near threshold) luminance. Target detection or dial reading at levels well above threshold probably present no significant problems during acceleration.

The effect of acute hypoxia on mental processes is a complex interaction. Figure 10-39 represents the effects of hypoxemia on several central processes. Comparison with Figure 10-38a indicates that with the exceptions of attention and fatigue, intervening mental processes are less sensitive to hypoxemia than are sensory visual processes. There is recent indication that acute exposure to 8,000 ft oxygen equivalence can result in decrease of complex reaction time during early learning of the skill (142). Visual performance becomes unacceptable above 13,000 feet; attention and fatigue above 15,000 feet; and the other intervening processes only above 19,500 feet, which is a physiologically unacceptable altitude.

The effect of hypoxia before and during exercise on maximum work output is seen in Tables 10-18 and 10-19 and the accompanying text. Such data are of value in planning for operational requirements after hypoxia emergencies.

The nature and treatment of the clinical syndromes during and immediately following hypoxic exposures have been covered by a recent review (42).

Hyperoxia

The unusual atmospheres proposed for space cabins have usually included an elevated partial pressure of oxygen. Table 11-8 summarizes the results of human experiments in these atmospheres. (See Inert Gas, No. 11.)

There is a wide spectrum of time-dependent symptoms of oxygen toxicity. (124, 213). Figure 10-40 indicates the time and pressure dependence of oxygen toxicity. The ordinate is partial pressure of oxygen. The abscissa is time to first symptoms. At high pressures of several thousand millimeters Hg, symptoms occur within 10 minutes and these are mostly of the central nervous system. In the zone of 1 atm. to 1/2 atm., the first symptoms are usually of the respiratory tract, such as bronchitis and pulmonary edema. Below 1/2 atm., the symptoms are variable. Atelectasis or alveolar collapse is seen in susceptible subjects, especially in the presence of high g loads. This is manifested by pains in the chest exaggerated by deep inspiration.

Human susceptibility to atelectasis in atmospheres of low pressure and high % oxygen appears to be a function of the collapsibility of terminal bronchioles in deep expiration (69) and may be associated with destruction of surfactant (212, 213). The airway conductance (liters/sec per cm of H_2O pressure per liter of lung volume) ranges from 0.14 to 0.35 in normal subjects but is down to 0.11 to 0.13 in subjects susceptible to atelectasis in 100% oxygen at 5 psia. With more studies, these data could possibly be used in the selection

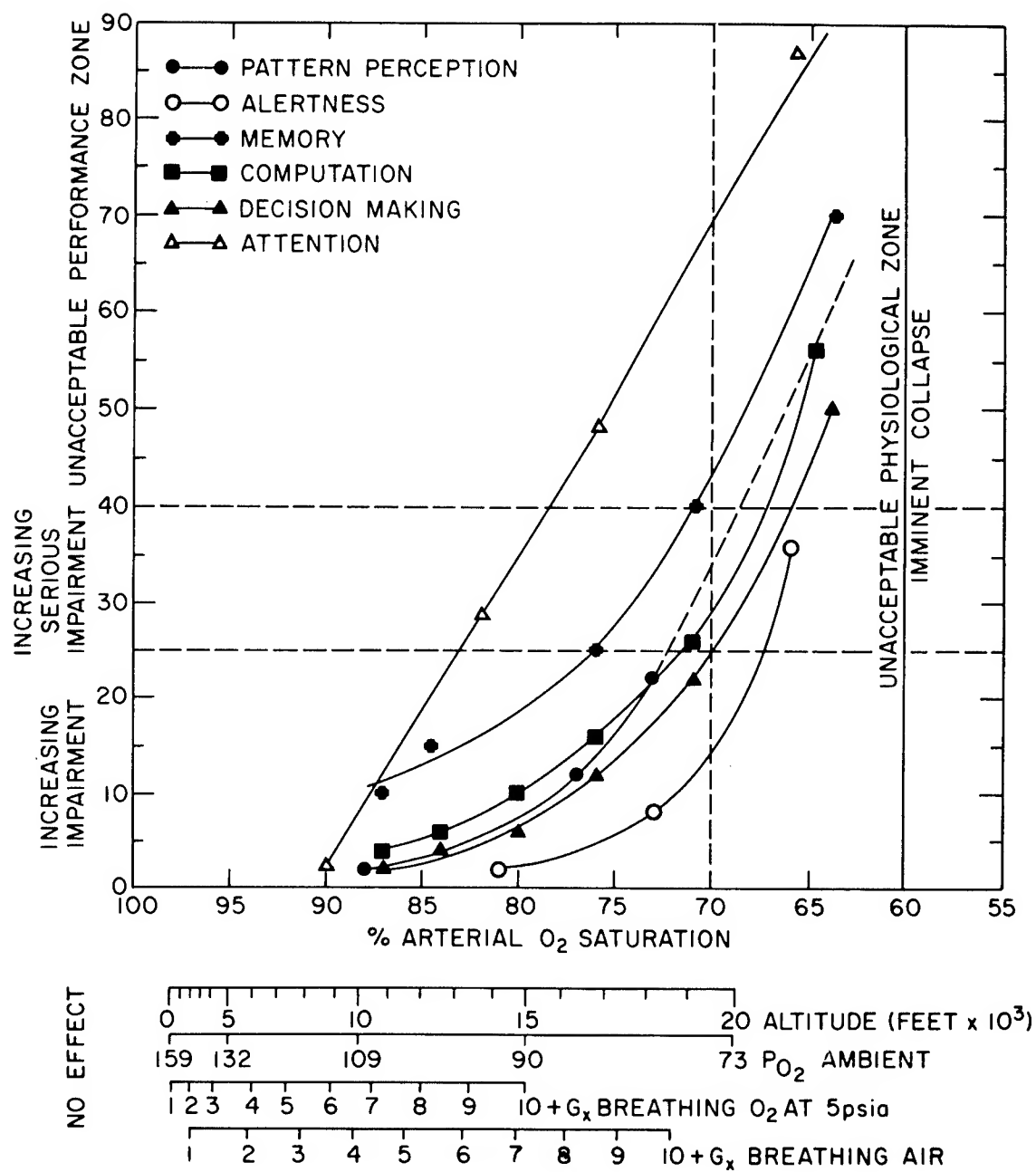


Figure 10-39

Effects of Hypoxemia on Some Intervening Mental Processes

(After Teichner and McFarland⁽²⁴⁶⁾ from the data of
McFarland⁽¹⁵³⁾ and Bills⁽²⁷⁾)

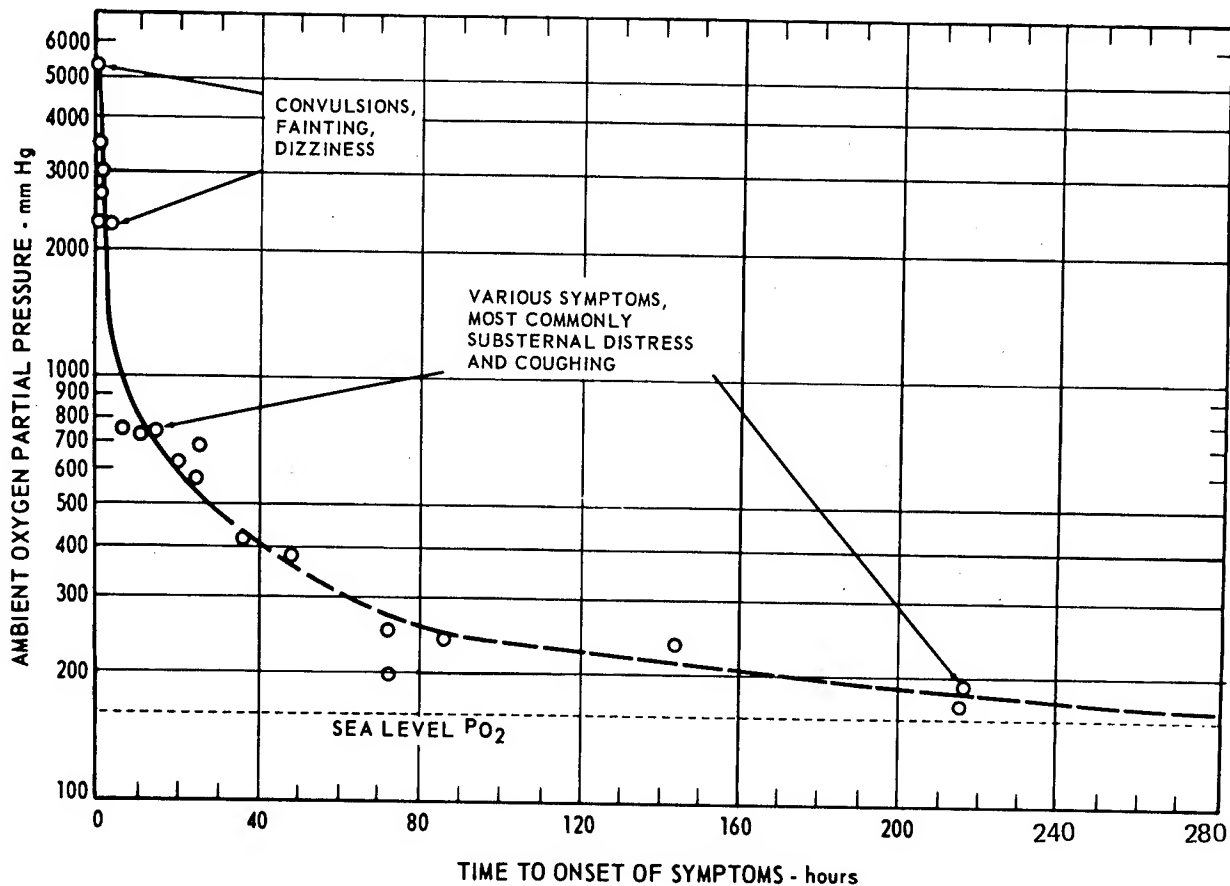


Figure 10-40

Times to First Symptoms of Oxygen Toxicity

(Adapted from Welch et al⁽²⁵⁹⁾, Bean⁽²²⁾, and Roth⁽²¹³⁾)

of astronauts for resistance to atelectasis. Aural atelectasis is also a problem in 100% oxygen environments, but has not proved to be such during actual space flights (213).

Table 10-41 summarizes the hematological changes found in the early missions of the Gemini program. Interpretation of the volume changes are presented on pages 7-110 to 7-125 of the zero gravity section in Acceleration, (No. 7). The role of 100% oxygen in producing the reduction of red blood cells is not clear. Hemolysis of red cells with oxidative changes in the hemoglobin has been seen in one simulated study in 100% oxygen at reduced pressures (111) but not in all studies (213). In Gemini operations, the reduction in red-cell mass of up to 15-20% shown in Table 10-41 was accompanied by no evidence of hemoglobin oxidation (24). Other studies have shown reduction of tocopherol and increase in the lipid peroxides of the blood of Gemini astronauts suggesting a tocopherol-deficiency, hemolytic anemia (28, 124, 172, 173, 196). The relative roles of tocopherol deficiency, restraint, and weightlessness in the production of the anemia are not clear (124, 212). Tocopherol factors have been covered in Nutrition, (No. 14).

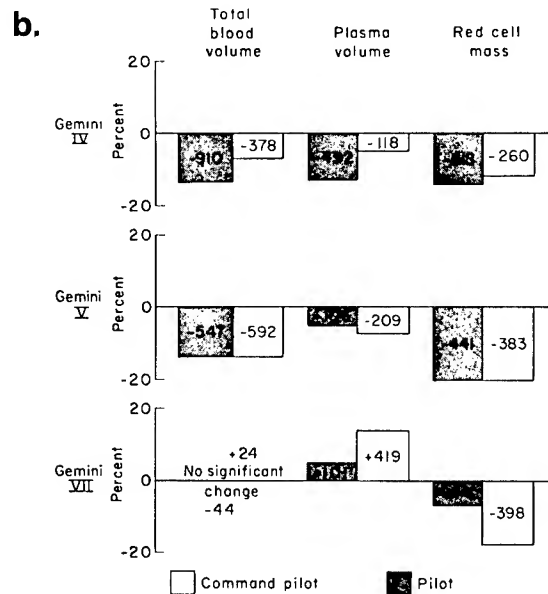
Table 10-41

Summary of Hematologic Findings from Gemini IV, V, and VII Missions

a.

	GT4	GT5	GT7
Days	4	8	14
Hematocrit	N	N	N
Reticulocytes	-	↓	N
Total Blood Volume	↓	↓	N
Red Cell Mass	↓8%	↓20%	↓19%
T _{1/2} CR ₅₁	-	↓	↓
WBC	↑	↑	↑
Osmotic Fragility	-	-	↑
Serum Bilirubin	-	N	N
Liver/Spleen Scan Ratio	-	-	↑30%

(After Kaplan et al⁽¹²⁴⁾)

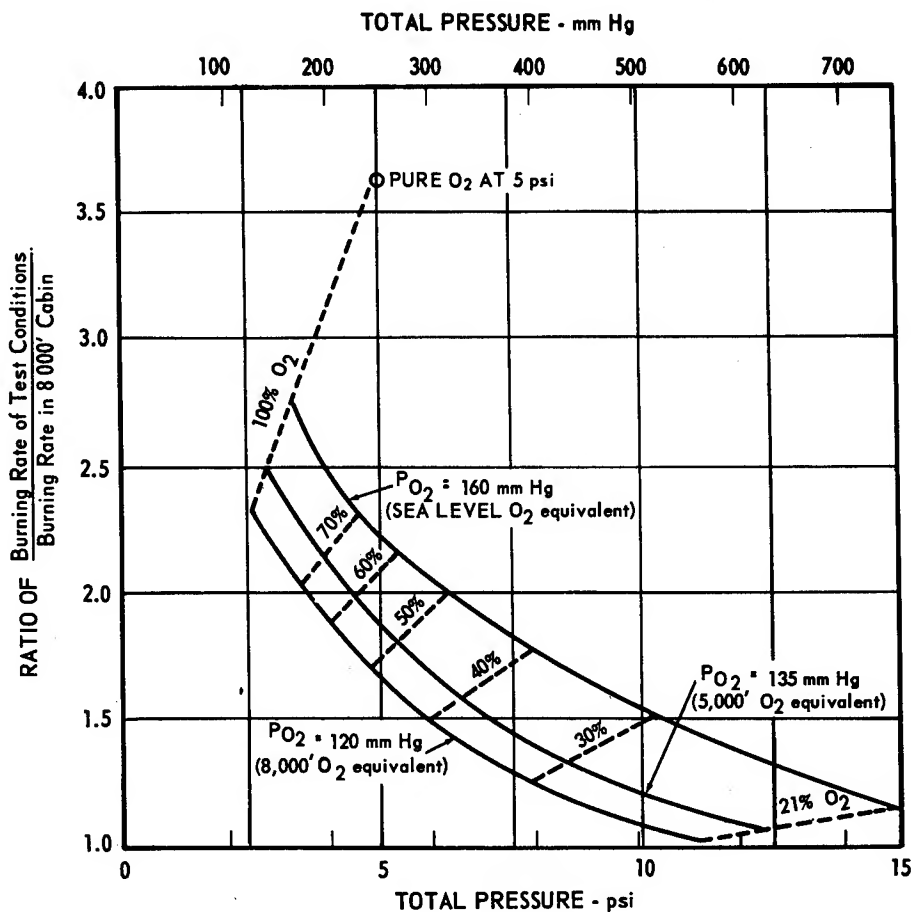


(After Berry et al⁽²⁴⁾)

Electron microscopic studies of damage to liver and kidneys of animals exposed to 5 psia - 100% oxygen are underway (78, 133, 167, 234). The relation of mitochondrial and other changes to human toxicity is not as yet clear.

Oxygen and Fire Hazards

One of the most serious effects of high partial pressure of oxygen in a space cabin is the fire hazard. Damage may be to both the spacecraft and crew. Data are available on the multifactorial aspects of the fire hazard in space cabin environments with high percentage of oxygen (118, 119, 214). Figure 10-42 represents the burning rate of cotton fabrics in different nitrogen-oxygen mixtures. Preliminary data are available on the damping effect by zero gravity on burning rate of insulated electrical wires in different gas mixtures (235). Mechanisms in the combustion of plastics are under study. (150)



Burning rate of cotton fabric is only one of many approaches to quantitation of fire hazard. In the graph, the burning rates in atmospheres of varied total pressure and percentage O₂ are compared with those in a standard aircraft cabin at 8,000 feet. Oxygen isopleths are shown for three partial pressures. The diluent effect of inert gas (nitrogen) is apparent.

Figure 10-42
Burning Rates of Cotton Fabrics

(After Klein⁽¹³²⁾)

In any gas mixture, the rate of burning of a solid is determined by the following oxygen-sensitive equation (118):

$$r = \frac{1}{d(c_s \rho_s - q_s / T_P)} \sqrt{\frac{Q}{M} \frac{k \rho D f_{O_2}}{T_m} \log \frac{T_m}{T_P}} \quad (22)$$

r = rate of flame spread

d = sheet thickness

c_s = heat capacity of solid

ρ_s = density of solid

q_s = heat released per unit volume of solid

T_P = pyrolysis temperature of solid

Q = heat of combustion per mole of O_2

M = molecular weight of gas (avg.)

k = thermal conductivity of gas

ρ = density of gas

D = diffusion coefficient of gas

The theory of flame spread over the surface of solid structures in oxygen and inert environments is now under study (150).

Regardless of the inert diluent present, the rate of burning is a function of the heat capacity of the mixture/per mole of oxygen present. The critical heat capacity per mole of oxygen above which flame will not propagate is determined by (118):

$$\log \frac{(C_p)_{crit.}}{[C_{p(O_2)} + n C_{p(x)}]} = kr \quad (23)$$

$(C_p)_{crit}$ = critical heat capacity of mixture per mole of O_2

$C_{p(O_2)}$ = heat capacity of O_2

n = number of moles of inert gas per mole of O_2

k = slope factor (gas dependent)

r = rate of flame spread

Table 10-43 represents for several candidate atmospheres, the physical properties which determine the rate of burning. It can be seen from Table 10-43 that nitrogen mixtures have a higher heat capacity as well as a higher heat capacity per mole of oxygen, factors which are critical in establishing burning rates. Table 10-44 represents the critical C_p values for several

Table 10-43
Thermal Properties of Gas Mixtures at 25°C
(After Huggett et al⁽¹¹⁸⁾)

Gas mixture	Heat capacity (cal/mole °C)	Heat capacity (cal/mole O ₂ °C)	Thermal conductivity (cal/(cm ²) (sec.) (°C/cm))	Thermal diffusivity at test condition (cm ² /sec.)	Partial pressure of oxygen at test condition (mm Hg)
21% O ₂ -79% N ₂	6.96	33.1	5.8 x 10 ⁻⁵	0.186	160
20% O ₂ -80% He	5.38	26.9	24.0 x 10 ⁻⁵	0.995	152
46% O ₂ -54% N ₂	6.99	15.2	5.8 x 10 ⁻⁵	0.372	175
46% O ₂ -54% He	5.90	12.8	15.6 x 10 ⁻⁵	1.178	175
70% O ₂ -30% N ₂	7.01	10.0	5.9 x 10 ⁻⁵	0.567	181
70% O ₂ -30% He	6.41	9.2	10.5 x 10 ⁻⁵	1.092	181
100% O ₂	7.02	7.0	5.9 x 10 ⁻⁵	0.567	258

Table 10-44
Critical Flame Spread Conditions
(After Huggett et al⁽¹¹⁸⁾)

Material	C _p (crit.) cal./°C mole O ₂	Critical Inert Diluent Concentration	
		mole % N ₂	mole % He
Wood	35.0	80.2	84.8
Paper	45.0	84.5	88.4
Cellulose Acetate	27.0	73.3	80.1
Cotton Fabric	36.0	80.6	85.4
Foam Cushion	17.5	60.3	68.0
Plastic Coated Wire	21.2	65.0	74.0
Painted Surface	27.0	73.3	80.1

combustible materials which would be present in a space vehicle and the critical inert diluent concentration required to attain the critical C_p level. The critical concentrations are higher in He-O₂ mixtures than in N₂-O₂.

The thermal conductivity of the helium-oxygen mixture is greater - another factor which controls ignition and burning rates. Tests indicate that the rate of burning of carbonaceous solids is somewhat more rapid in helium atmospheres than in nitrogen atmospheres of the same percent composition (118). (See also Table 10-44.) The rate of flame spread at constant atmospheric composition is approximately independent of pressure over the range studied (258-760 mm Hg).

In contrast to rate of propagation of flame, the ignition energy required to ignite carbonaceous solids is greater in helium than in comparable nitrogen mixtures. Table 10-45 represents these differences which are minor except

Table 10-45
Energy Required for Ignition of Materials in Various Atmospheres
(Cal/cm²)
(After Huggett et al⁽¹¹⁸⁾)

Atmosphere	Air	20% O ₂ 80% He	46% O ₂ 54% N ₂	46% O ₂ 54% He	70% O ₂ 30% N ₂	70% O ₂ 30% He	100% O ₂
Pressure	760 mm	760 mm	380 mm	380 mm	258 mm	258 mm	258 mm
Wood	25 ± 1	109 ± 11	25 ± 2	24 ± 0.5	25 ± 1	22 ± 1	23 ± 1
Paper	32 ± 1	39 ± 0.5	25 ± 2	26 ± 0.5	26 ± 0.5	25 ± 0.5	25 ± 1
Cotton Fabric	13 ± 0.5	NI	12 ± 0.5	17 ± 0.5	15 ± 0.5	16 ± 0.5	15 ± 0.5
Plastic Wire	20 ± 1	NI	16 ± 1	NI	17 ± 1	46 ± 1	16 ± 1
Painted Surface	30 ± 1	NI	56 ± 5	70 ± 4	61 ± 3	57 ± 5	36 ± 1

for the important ignition of plastic-coated electrical wire by current heating. The slightly higher ignition energies required to ignite different carbonaceous solids in comparable mixtures of helium-oxygen than in nitrogen-oxygen when a radiant heat source is used appears to be related to the sample surface. Samples of low specific surface and low thermal diffusivity such as wood show little atmosphere dependence. As the specific surface is increased as with paper and cotton fabrics, energy loss to the atmosphere is increased. In the case of thin layers of combustible materials on a support of high thermal conductivity, the energy loss is even greater and such fires are difficult to start in helium-oxygen. For any given electrical energy, the equilibrium temperature of an ignition wire will be lower in this atmosphere.

Data on the rate of burning of plastics clothing and integumentary structures in high oxygen environments and optimum extinguishing procedures in sub and zero gravity are now being gathered (1, 2, 54, 59, 60, 89, 128a, 136, 150).

A design guideline for use of non-metallic materials in spacecraft is now in preparation (89).

Carbon Dioxide

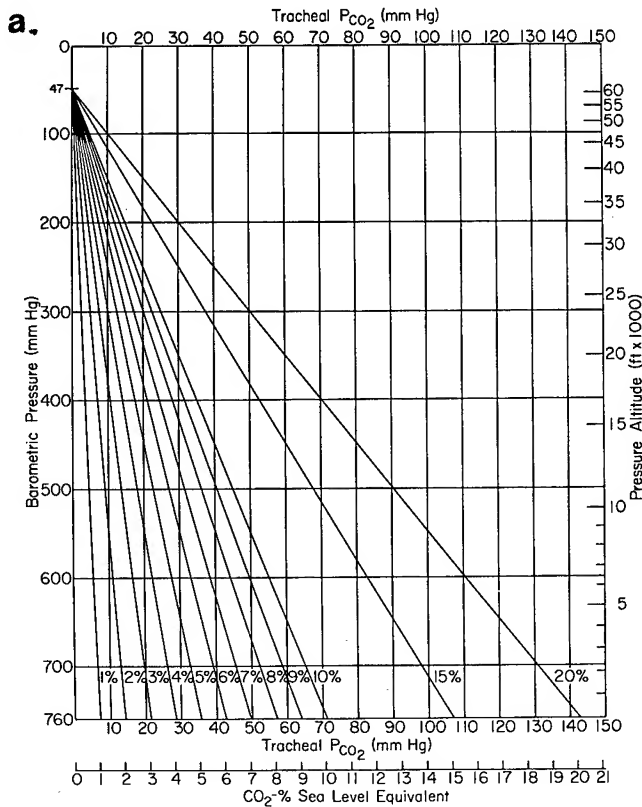
Toxic exposures to CO₂ as a result of failure of CO₂ absorption or use of CO₂ fire extinguishers may occur at altitude. Most data on CO₂ toxicity are recorded as dry gas at sea level conditions. Figure 10-46 a and b allows one to determine quickly the dry percent of CO₂ in a gas mixture at altitude that will give the same partial pressure in the lung (calculated as the equivalent P_{CO₂} in the tracheal mixture of CO₂, N₂, O₂, and water) as does a given percentage of CO₂ in inspired air at sea level. Figure 10-46b is an expanded scale of the lower barometric pressures which can be used in evaluating CO₂ effects in space helmets and cabins.

The toxic effects of CO₂ (given as % CO₂ at sea level in the atmosphere) are summarized in Figure 10-47a and b. Figure 10-47c gives the range of

Figure 10-46

Carbon Dioxide Equivalents at Altitude

(After Luft⁽¹⁴⁵⁾)



a. Sea-Level Equivalents of Given
% CO₂ at Altitude

b. Expansion of Figure a, in Regions
of Lower Pressure

Data is more easily used for calculation
of sea-level equivalent CO₂ in helmets
of space suits.

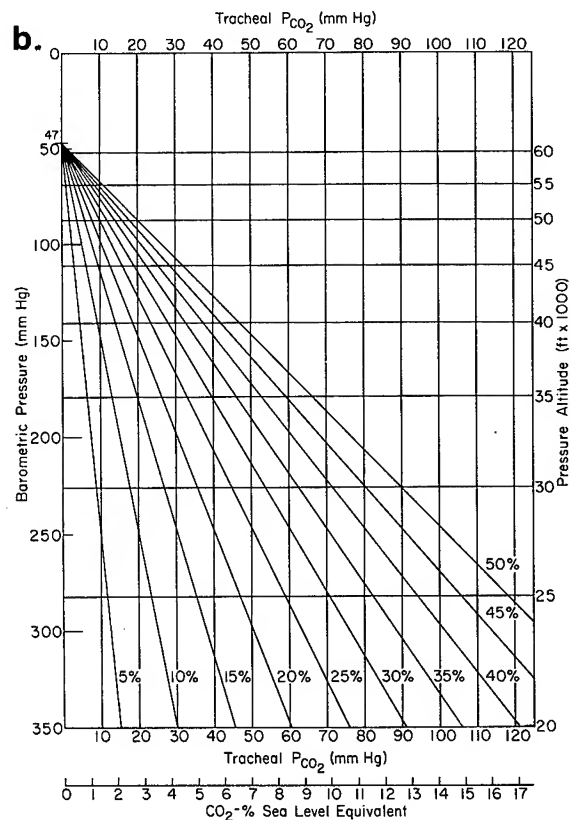


Figure 10-47

Symptoms and Thresholds of Acute and Chronic Carbon Dioxide Toxicity

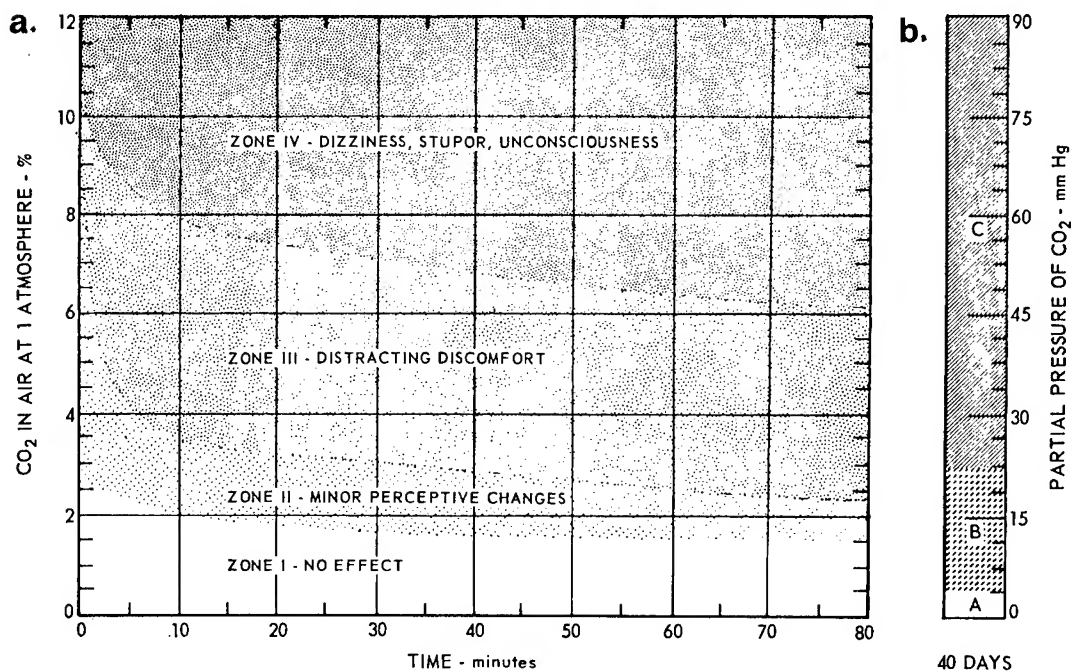


Chart a shows the general symptoms common to most subjects when exposed for the times indicated to mixtures of carbon dioxide in air at a total pressure of 1 atmosphere. In Zone I, no psychophysiological performance degradation, or any other consistent effect, is noted. In Zone II, small threshold hearing losses have been found and there is a perceptible doubling in depth of respiration. In Zone III, the zone of distracting discomfort, the symptoms are mental depression, headache, dizziness, nausea, "air hunger," and decrease in visual discrimination. Zone IV represents marked deterioration leading to dizziness and stupor, with inability to take steps for self-preservation. The final state is unconsciousness.

The bar graph b shows that for prolonged exposures of 40 days, concentrations of CO₂ in air of less than 0.5% (Zone A) cause no biochemical or other effects; concentrations between 0.5 and 3.0% (Zone B) cause adaptive biochemical changes which may be considered a mild physiological strain; and concentrations above 3.0% (Zone C) cause pathological changes in basic physiological functions and performance.

Table c gives the symptoms in 39 resting subjects who inhaled CO₂ for 15 minutes at the noted concentrations.

(Figures a and b after Roth and Billings⁽²¹⁶⁾, adapted from the data of King⁽¹³⁰⁾, Nevison⁽¹⁸⁵⁾, and Schaefer⁽²²¹⁾; c after Schaefer et al⁽²²⁸⁾)

	3. 3% CO ₂	5. 4% CO ₂	7. 5% CO ₂
Dyspnea	2	4	24
Headache	0	0	15
Stomach ache	0	0	1
Dizziness	0	0	6
Sweating	1	1	5
Salivation	0	0	1
Numbness of extremities	0	0	5
Cold sensations	1	1	3
Warmth sensations	1	1	4
Increased motor activity	0	0	10
Restlessness	0	0	10
Loss of control over limbs (overactivity)	0	0	4
Loss of balance (spatial disorientation)	0	0	7
Color distortion	0	0	2
Visual distortion	0	0	6
Irritability	0	0	4
Mental disorientation	0	0	2

symptoms experienced after exposure to different concentrations of CO₂. It is recommended that for long periods of time, the P_{CO_2} of a cabin be maintained below 4 mm Hg or 0.5% sea level equivalent (SLE); and for emergencies of less than 2 hours, the level of 15 mm Hg or 2.0% (SLE) not be exceeded. If possible, environmental control systems of space suits should be designed to maintain space suit helmet CO₂ below 1% (SLE) or 7.5 mm Hg. This would allow for some CO₂ accumulation and yet have the level of inspired CO₂ kept well below that which could adversely affect the astronaut at high work loads. As a maximum for several hours exposure, the helmet P_{CO_2} should not exceed 15 mm Hg during periods of stress.

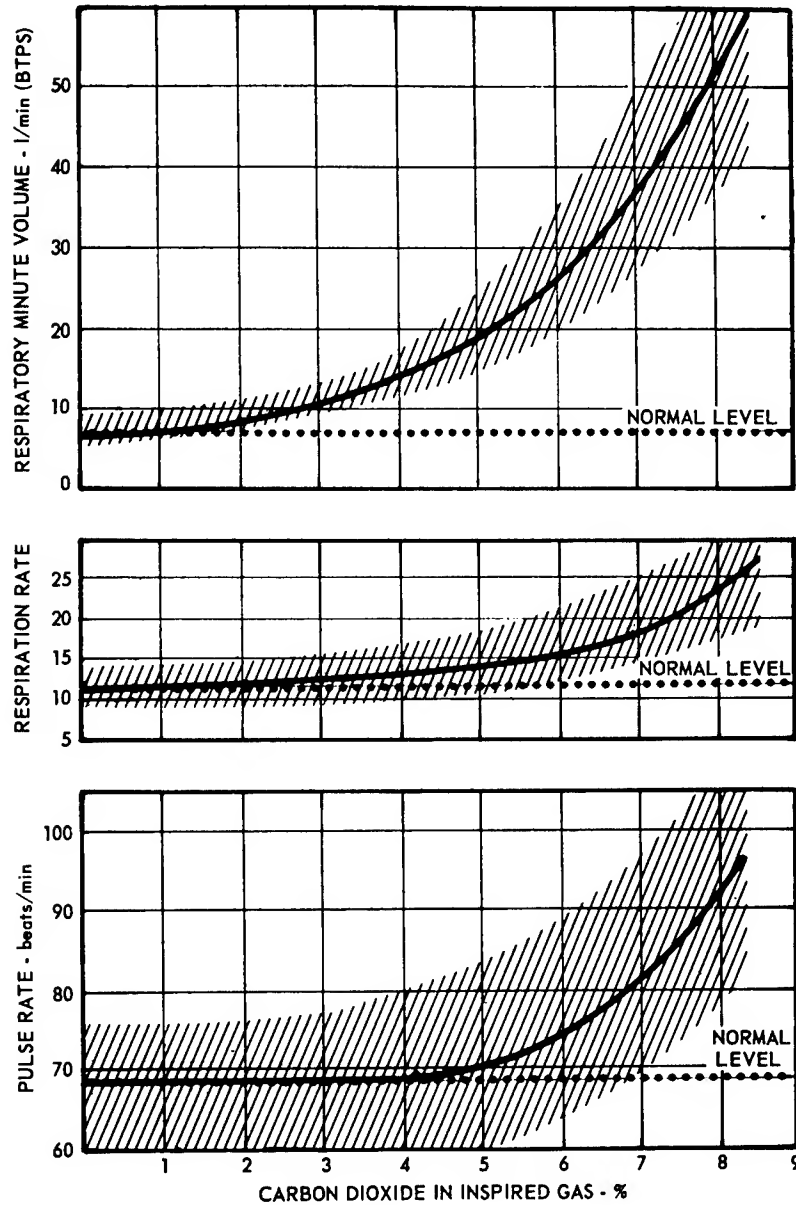
From test data gathered during manned qualification test and crew training runs with the Gemini EVA chestpack (ELSS), the partial pressure of the carbon dioxide in the inspired gas ranged from 7 to 13 mm Hg for work rates up to approximately 2400 BTU/hr (156). This range was, of course, subject to considerable variation, depending on the ELSS flow mode (medium, high, medium-plus-bypass, or high-plus-bypass) and the associated work levels. Although carbon dioxide control was accomplished by dumping gas from the suit loop, its washout was dependent upon the amount of gas being dumped; that is, if the primary gas flow rate was increased, the ventilation flow rate would increase proportionally, and the overboard flow would increase by the same amount as the primary. Carbon dioxide control was also dependent upon flow rate of fresh gas to the helmet oro-nasal area, or upon the suit ventilation efficiency. Modifications in one or both of these areas would have been required to reduce the level of inspired carbon dioxide, but since normal design workloads did not produce critical concentrations of carbon dioxide, these modifications were apparently not needed. At workloads well beyond the design limits, carbon dioxide concentrations may be objectionably high. A high carbon dioxide concentration may have contributed to the sudden fatigue and heavy respiration of the pilot during the Gemini XI umbilical EVA.

The cardiorespiratory response to CO₂ is a key factor in CO₂ toxicity. Figure 10-48a notes the cardiorespiratory response to carbon dioxide given in % (SLE). Respiratory minute volume appears to be most sensitive to CO₂. The population response characteristic appears to account to some degree for variations in tolerance to CO₂. It has been demonstrated that individuals with a relatively large tidal volume and slow respiratory rate show less of a respiratory and sympathetic nervous system response, and less symptoms while breathing low concentrations of CO₂ than individuals with a relatively small tidal volume and fast respiratory rate (227). Accordingly, knowledge of responses to CO₂ might have some practical value from a monitoring standpoint. An average effect of various inspired air-CO₂ mixtures upon the steady-state alveolar minute ventilation and partial pressure of CO₂ of normal resting man at sea level is shown in Figure 10-48b. It demonstrates the increasingly inadequate ventilation, notably paralleled by an accelerating rise of alveolar CO₂, as the ambient CO₂ increases. This dulling of man's ventilatory response to progressively increasing levels of CO₂ has been attributed to a combination of the narcotic effect of CO₂ on respiratory center neurons, the stimulation of pressure receptors in the thorax by hyperventilation and the fatiguing of respiratory muscles (65). Increasing the P_{O_2} of the breathing mixture decreases the sensitivity; and decreasing the P_{O_2} increases the sensitivity of the respiratory center. By stimulating ventilation with a

Figure 10-48

Cardiorespiratory Response to Carbon Dioxide

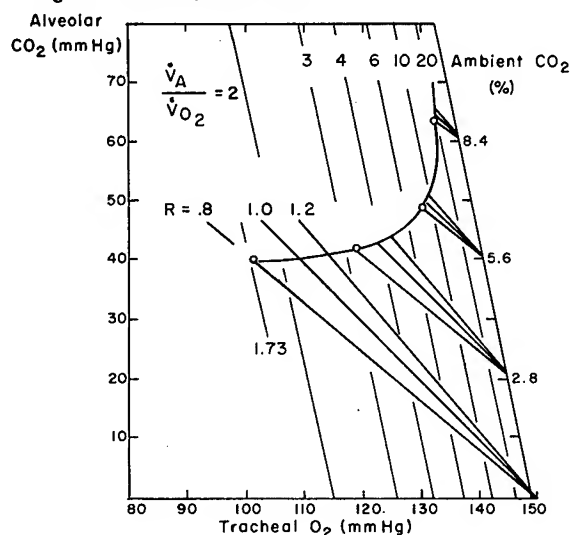
- a. Ranges of Response of Normal Population to Acute Elevation of CO₂



The immediate effects of increased CO₂ on pulse rate, respiration rate, and respiratory minute volume are shown for subjects at rest. The hatched areas represent one standard deviation on each side of the mean. To convert percentage of CO₂ to partial pressure, multiply fraction of CO₂ by 760 mm Hg.

(After Roth and Billings⁽²¹⁶⁾ adapted from Schaefer et al⁽²²⁸⁾ and Dryden et al⁽⁶⁷⁾)

Figure 10-48 (continued)



b. Effect of Inspiring Various CO₂-Air Mixtures Upon the Steady State Alveolar Gas Composition of Normal Man at Rest

The ratio V_A/V_{O_2} represents liters (BTPS) per minute of alveolar ventilation for every 100 ml(STPD) of oxygen consumed per minute. R represents the respiratory exchange ratio (volume of CO₂ output for volume of O₂ intake) and would be equal to the respiratory quotient (RQ) under steady state conditions at sea level.

(After Fenn⁽⁸¹⁾, calculate from equations of Gray⁽¹⁰⁰⁾)

proper amount of CO₂ in the inspired air, the alveolar oxygen tension can be somewhat increased, and so performance and well-being at moderate altitudes maintained. However, since the major factor underlying this phenomenon is mainly the displacement of nitrogen in alveolar air by CO₂, with an associated elevation of the alveolar oxygen tension due to increased ventilation, it is readily apparent that CO₂ can not confer any protection from hypoxia in a pure oxygen space atmosphere (146). Moreover, it is doubtful if this effect could exist to a significant degree in proposed space atmospheres, which have a much lower inert gas percentage than does air (145).

Acute CO₂ Toxicity

The pathophysiology and the treatment of the various clinical syndromes resulting from acute and chronic CO₂ toxicity in space operations has been recently reviewed (42). Much of the following section is taken directly from this study. Rough calculations based on current suit data indicate that an astronaut who is walking on a lunar or planetary surface can increase his inspired CO₂ to a highly toxic level, within one to two minutes after a complete cessation of CO₂ absorption by his extravehicular life support system. Carbon dioxide storage by the body would have a significant retarding effect on rates of atmospheric CO₂ accumulation only in such a small rebreathing volume as that of a space suit (76, 86). In fact, recent evidence indicates that the immediate storage of CO₂ involves a body compartment with a volume corresponding to that of the extracellular space (86, 183). Carbon dioxide storage by the body should therefore be taken into account when attempting to predict such rates accurately. It is estimated that three astronauts who are carrying out normal intravehicular operational tasks would not, even in the confined volume of the Apollo Command Module, experience symptoms of CO₂ toxicity until about 6 to 7 hours after CO₂ removal from their atmosphere ceases (42). From such considerations, then, one can foresee the possibility of toxic levels of CO₂ being reached over a period of minutes in space suit atmospheres and over a period of hours in spacecraft cabin atmospheres.

The cardiorespiratory response to acute elevation of CO₂ has been covered above and in greater detail in Reference (42). Carbon dioxide levels in the body increase during sleep (29, 40, 42). The majority of normal individuals remain asleep until the ambient CO₂ reaches 4 percent or their alveolar CO₂ reaches 50 mm Hg. An astronaut exposed to an increasing level of inspired CO₂ while asleep may, on awakening, suffer from the clinical manifestations which can accompany CO₂ withdrawal. (See below.)

An elevated level of inspired CO₂ can lead to a decrease in body temperature, even in a comfortable or warm, high-humidity environment (35, 38, 219). A 1 to 3°F decrease in body temperature, with associated chilly sensations was noted during, and for many minutes after subjects breathed about 5 percent CO₂, which accumulated in their 72° to 77°F environment over a period of several hours (35). This lowering of the body heat store may be due to a combination of a number of CO₂ effects on the body. Increased heat loss will result from CO₂-induced cutaneous vasodilatation and hyperventilation (39, 219). A marked increase in sweating also accompanies acute exposures to toxic levels of CO₂ (35, 227). This phenomenon may be due to a lowering of the thermostatic setting of the hypothalamus, an increased sensitivity of cutaneous thermoreceptors, an increase in sympathetic nervous system activity, or an augmentation of sweat-gland effector activity (38). It has also been shown that toxic levels of CO₂ markedly suppress shivering which follows exposure to a cold environment (39). An acutely elevated CO₂ concentration could therefore increase an astronaut's susceptibility to cold, leading to a lowering of body temperature and associated symptoms sufficient to reduce his functional capacity.

The sympathetic response to CO₂ appears to be primarily responsible for preventing orthostatic intolerance both in subjects who breathed 4 to 7 percent CO₂ for varying periods of time after exercise and in quadriplegics who breathed 5 percent CO₂ during tilting (64, 169). However, it cannot be stated with certainty if CO₂ accumulation in an astronaut's ambient atmosphere would enhance his susceptibility to or protect him from orthostatic intolerance on return to a gravity environment, especially if he has sustained some degree of cardiovascular deconditioning during his exposure to weightlessness (42).

The diuresis produced by even low toxic levels of CO₂ is a physiologic reaction which might conceivably have adverse effects on an astronaut. Exposure of normal recumbent subjects to 5 and 7 percent CO₂ produced a three-fold increase in urine output over and above the normal diuretic response to recumbency (21). Also, exposure to 5 percent CO₂ for over 3 hours without replacing the fluid loss could lead to marked hemo-concentration. This response may result from stimulation of intravascular stretch receptors in the left atrium and pulmonary vessels through a CO₂-induced increase in central blood volume, by some mechanical action on the atrial wall from exaggerated respiratory movements, or by an increase on the atrial transmural pressure gradient (42, 252). If one or more of these mechanisms does operate to some degree, afferent connections from these receptors would inhibit the production of antidiuretic hormone by the neurohypophysis. Since voluntary hyperventilation, with alveolar CO₂ being maintained constant by inhaling a 2 percent mixture, has been shown to produce much less of a diuresis than CO₂

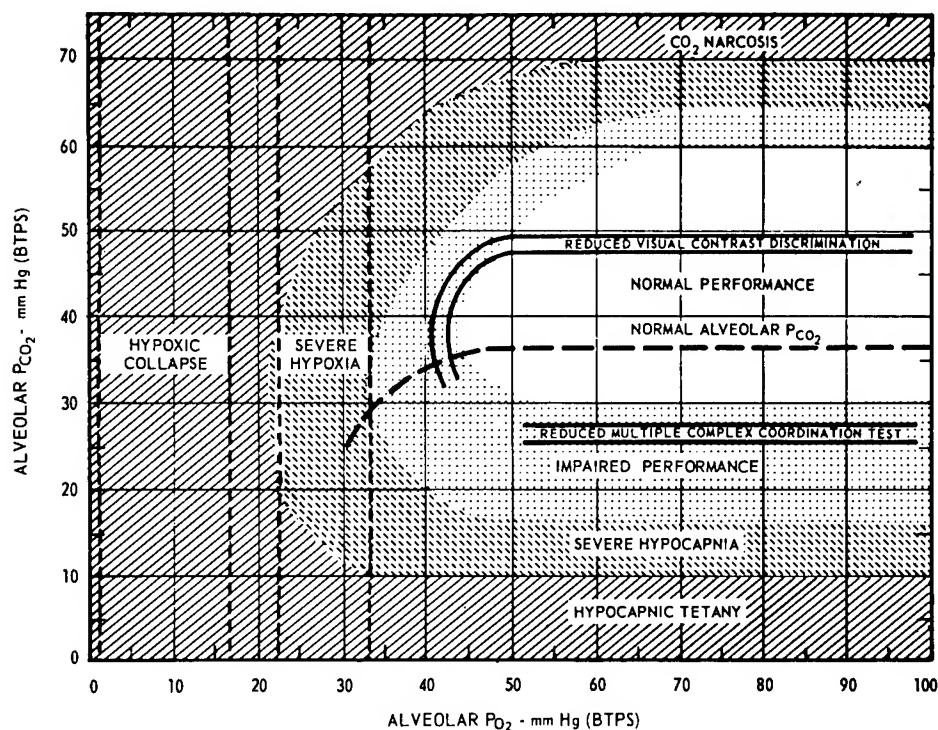
alone, it is also likely that CO₂ acts directly on the neurohypophysis or on the renal tubule (251, 252).

Since CO₂ exerts such a marked diuretic effect on man in the recumbent position, it is probable that this effect would be of similar, if not greater magnitude in the weightless environment (42). Study of the diuretic response to various concentrations of CO₂, especially with the exposed individual performing at various work loads, is indicated before potential hazards of such a diuresis can be implied. One would think that if a significant diuresis can occur at relatively asymptomatic levels of CO₂, exposure of an astronaut in a space suit to such levels might limit the duration of his extravehicular activity by virtue of a need to void urine. It should also be kept in mind that vasodilation and excess loss of body fluid may decrease tolerance to heat and cold and increase the orthostatic intolerance of an astronaut entering a gravity environment. (See zero gravity in Acceleration, No. 7.) The effect of combined CO₂ and heat stresses on man has apparently not been determined (42).

Figure 10-49 represents the combined effects of oxygen and carbon dioxide on general physiological effects and performance. The collapse level of 22 mm Hg P_O₂ given for PACO₂ of 20-40 mm Hg probably represents some degree of acclimatization in that the usual level for hypoxic collapse of un-acclimatized individuals is about 30 mm Hg PAO₂ (13).

The effects of carbon dioxide on exercise tolerance is a key factor in spacesuit emergencies (42). Data in the literature regarding the relationship of concentration to work degradation have been quite equivocal (20, 55 96, 103, 116, 117, 122, 135). Variable experimental conditions may play a role. These data suggest that work output and motor performance may be limited by dyspneic responses at sea level equivalents of 2-3% of inspired CO₂. Preliminary studies suggest that at 2% CO₂ (15 mm Hg), given acutely, maximum aerobic capacity is reduced by 13% (83). Three out of 12 subjects at this level of CO₂ reported "suffocating sensations" at maximum work levels while none of the controls on air did so. Current studies are focused on performance and electrolyte changes in simulated carbon dioxide exposures (93, 95, 145). The duration of exposure to CO₂ may be a factor in exercise tolerance.

Since exercise appears to markedly affect man's tolerance to CO₂, one would not expect the results of resting exposures to be applicable to a situation in which an astronaut is exposed to elevated levels of inspired CO₂ while having to perform work, such as during extravehicular operations in space. It is also quite apparent that past experiments have actually yielded very little information on the time of onset and the degree of functional impairment which occurred during and in the immediate period after various acute exposures to CO₂. Although past experiments have yielded enough information for reasonable recommendations of maximum allowable levels of CO₂ for acute exposures to this gas in space, confirmatory data should be obtained in studies which simulate possible modes of exposure during operations in space, especially during various work loads in extravehicular activity.



This graph shows the relationship of alveolar O_2 and CO_2 composition to performance. The scales are partial pressures of the two gases, at body temperature and pressure, saturated with water (BTPS). Above the dashed line labeled "normal alveolar CO_2 " are zones of increasing hypercapnia, limited by the zone of CO_2 narcosis. Below the dashed line, marked as zones of increasing hypocapnia, are lower levels of alveolar CO_2 , which are commonly the result of excessive respiratory ventilation. The left side of the graph shows low levels of alveolar PO_2 , labeled zones of "severe hypoxia" and "hypoxic collapse," and these hypoxic zones combine with hyper- or hypocapnia to affect performance as shown.

Normal performance is seen when the gas tensions fall in the clear area; impaired performance in a hand-steadiness test is shown by shading, and the results of two other performance tests are plotted also to indicate the variation to be expected when "performance" is variously measured.

Figure 10-49

Human Performance Under Abnormal O_2 and CO_2 Conditions

(After Roth and Billings⁽²¹⁶⁾, adapted from Otis et al⁽¹⁸⁹⁾, with additional data from Balke⁽¹⁷⁾)

a. Behavioral Changes During Acute CO₂ Exposure

The decay in performance and symptoms noted by 39 normal resting subjects who were alternately exposed for 15 minutes to air and, in order, 1.5, 3.3, 5.4, and 7.5 percent CO₂ are recorded in Table 10-47c. No symptoms were reported at the 1.5 percent level. These symptoms usually appeared during the last 5 minutes of the 15-minute exposures to the indicated gas. Proficiency at card naming and sorting was unaltered during the exposure of 31 subjects to 5 percent CO₂ for 16 minutes. Although all of these subjects were moderately dyspneic, most reported fatigue, fogginess and an effort to concentrate; two experienced visual disturbances; and one failed to complete the last minute because of dizziness, marked dyspnea and impending fainting (261). It is noted that most of these individuals, many of whom were experienced pilots, were of the opinion that 5 percent CO₂ for a 16 minute period was close to a marginal concentration for the safe operation of an automobile or airplane (265). Other studies carried out at the 5 percent level have found a significant increase in the pain threshold and decrease in the fusion frequency of flicker (229, 237, 243).

Acute exposure to over 5% CO₂ gives variable symptoms affecting performance. Two observers who entered a 5.7 percent CO₂ atmosphere in which several individuals were tolerating a gradual increase of CO₂ immediately became so dyspneic that they were unable to make observations (35). Seven subjects tolerated 6 percent CO₂ for about 22 minutes, but experienced marked dyspnea, flushing and sweating of the face, and feelings of stupification and impending collapse, especially toward the end of the exposure (36). Visual intensity discrimination has also been shown to be affected in studies at the 6 percent level. Prolongation of the time required for addition and cancellation tests, and the existence of dissociation, perseveration and aberrant responses have been demonstrated in subjects breathing 6 to 7 percent CO₂ (91, 92).

In contrast to the symptoms reported in the above exposures to 6 percent CO₂, the "mental status seemed unaffected" in 7 subjects who breathed 7 percent CO₂ for 40 to 90 minutes, although all suffered from dyspnea and some complained of mild headache and burning of the eyes (34). Exposure to 7.5 percent CO₂ for 3.5 to 6 minutes has been tolerated, but symptoms had a shorter lag time than in 7 percent CO₂ (36). The 7.5 percent CO₂ level has also been found to decrease the inhibitory effect of light stimulation on brain waves (electroencephalographs) - a finding which demonstrated the depressive or narcotic action of CO₂ on the central nervous system (229). An experiment in which 42 subjects who breathed 7.6 percent CO₂ for 2.5 to 10 minutes yielded results similar to the other experiments near this CO₂ level, although one subject did lose consciousness (36, 228).

Individuals who have been exposed to 10 percent CO₂ have immediately experienced one or more of a number of clinical manifestations, such as extreme dyspnea, visual and auditory hallucinations, chilliness, nausea, and vomiting, a strangling sensation, burning of the eyes, cloudiness of vision and profuse sweating. They have usually become stuporous within 10 minutes and lose consciousness within 15 minutes (36, 42, 65, 80, 262). Although CO₂ concentrations of over 20 percent have been used for the treatment of mental disorders and experimentally for anesthesia, it is considered

probable that if an individual who does not have the benefit of therapeutic support is exposed to CO₂ levels above 10 percent, he will rapidly suffer the sequence of respiratory depression, convulsion, "shock," and death (104, 144, 262, 177).

Data are available on the subacute exposure to CO₂ (35, 36, 104). Most of these studies allowed CO₂ to accumulate in closed systems with P_{O₂} above the hypoxic level. On one study, the chamber CO₂ was increased linearly over an 8 hour period to 6.4 percent while oxygen decreased to 13 percent (104). At about 4 percent CO₂, the subject became aware of increased breathing and began to complain of headache and nausea. For the last two hours of exposure, when CO₂ had passed about 5.2 percent, breathing was "painfully labored and required so much exertion as to cause great exhaustion." This marked dyspnea eventually caused termination of the experiment. Another subject showed a similar response, having to end his 7 hours in the chamber after linear CO₂ and oxygen changes to 5.8 and about 14 percent, respectively. In bag rebreathing to a maximum concentration of about 10 percent, attained in about 1.5 hours, they suffered from mental confusion and extreme perspiration in addition to the manifestations described above, as this level was reached. Other studies at intermediate rates have yielded similar results (36, 42, 108, 248). Fatigue, listlessness, headache, chilliness, nausea, and vomiting were reported as concentrations of CO₂ increased much above about 5%.

b. CO₂ Withdrawal

Symptoms can be experienced after the cessation of certain exposures to CO₂ and, as the examples given below will show, can result in even greater functional impairment than symptoms experienced during exposure. This reaction and its marked variability was well demonstrated by a study in which 5 subjects breathed 6.7 percent CO₂ for one hour (5). On cessation of exposure, one subject immediately vomited repeatedly and complained of nausea and headache; two experienced temporary, severe, incapacitating headaches; and two complained of only slight headache. In other studies, subjects exposed to 3 percent CO₂ for many hours apparently complained of only a mild headache on returning to air (52, 225). Headache was also reported after exposures to 5.2 and 6.4 percent CO₂ for 2 hours. A frequent symptom after cessation of exposures to 7.6 percent CO₂ for an average of 7.4 minutes and 10.4 percent CO₂ for an average of 3.8 minutes was temporary dizziness (65). Similar clinical manifestations have also occurred after withdrawal from exposure to gradually increasing ambient CO₂ levels (35, 36, 42, 104, 108). It is unlikely, except under rescue conditions, that CO₂ exposures in space will ever be severe enough to cause such serious consequences of CO₂ withdrawal as prolonged profound hypotension and grave cardiac arrhythmias which are prone to occur following marked CO₂ retention in anesthetized patients (42, 99, 187, 198, 201).

The cause of the above clinical manifestations of CO₂ withdrawal is unknown. Headaches resulting from exposure to CO₂, which increased to 5 to 7 percent over one to 3 hours, were much worse, occurred with greater frequency, and lasted much longer in subjects who breathed air as compared

to those who breathed oxygen after exposure (108). Also, the brief hypotension which coincides with the temporary dizziness immediately after brief exposures to 7.6 and 10.4 percent CO₂ may be due to the vasodilatory action of CO₂ persisting beyond its sympathetic action in the immediate post-exposure period (65, 201). Other effects of altered sympatho-adrenal activity, which could accompany CO₂ withdrawal, might conceivably cause symptoms (42). Whether the temporary under shoot of alveolar CO₂, observed when 15-minute exposures to 5.4 and 7.5 percent CO₂ were terminated, might produce a hypocapnia of a sufficient magnitude to produce a symptom such as dizziness remains to be determined (228). Finally, it is conceivable that a cerebral vasomotor phenomenon caused by exposure to, then withdrawal from a CO₂ environment might be a major etiologic factor (219).

Certain symptoms which are not really specific effects of CO₂ withdrawal often occur in the post-exposure period. Marked general fatigue and soreness in the region of the diaphragm have been reported after most of the prolonged acute exposures to over 4 percent CO₂ described above. Such symptoms could no doubt limit an astronaut's physical work capacity for several hours after such an exposure. Also, intense shivering might be experienced after certain exposures to CO₂ (42).

There is at present no specific practical measure which might be used to combat the acute withdrawal effects of CO₂ on an astronaut (42). Since the acidosis accompanying acute CO₂ toxicity corrects itself within a few minutes, after even a prolonged acute CO₂ exposure, it is important to remember that the administration of a buffering agent to an astronaut who has suffered a severe exposure would probably not be effective. It would be more important to assure him adequate ventilation and to treat the consequence of possible associated hypoxia.

Chronic Carbon Dioxide Toxicity

Several causes of chronic carbon dioxide exposure lasting days to months can be envisaged. A spacecraft life-support system could malfunction for a prolonged period of time, possibly until the completion of a mission. Also, the upper limit of atmospheric CO₂ specified for a normally operating spacecraft life-support system may be too high, the decision for this limit being implied from ground-based studies which have been too short in duration to have elicited clinical manifestations. As well, an elevated partial pressure of CO₂ in space atmospheres may be needed to increase the efficiency of physical, chemical and biotic CO₂ scrubbers under emergency conditions (215). Table 10-47b summarizes the response to chronic effects of CO₂.

In assessing the possible clinical problems resulting from 90 days exposure to 1-1.5% CO₂ in submarines, minor physiological alterations were recorded on 23 men during the 42 days of exposure (220, 222, 230, 231, 232, 233). No alterations in basic physiologic parameters, such as blood pressure, pulse rate, weight and temperature, occurred. On the other hand, data on respiration, acid-base balance, calcium and inorganic phosphorus metabolism, adrenal cortical activity, and cardiovascular capacity revealed significant changes, some of which might have important clinical implications. Most of

the changes occurring in this study continued throughout the 9 day post-exposure study period; all had essentially returned to pre-exposure levels after 4 weeks of breathing air.

Alterations of blood and urine pH and urine CO₂ clearly indicated the existence of a phase of slight, uncompensated respiratory acidosis lasting for 23 days, followed by a phase of compensated respiratory acidosis for the remainder of the 42-day exposure (232). (See Table 10-50a.) The anatomical and physiological dead space, as well as arterial-alveolar CO₂ and O₂ gradients in Table 10-50b are shown to be increased during the exposure and

Table 10-50
Respiratory Acidosis from Chronic Exposure to 1.5% CO₂
(After Schaefer⁽²²⁴⁾)

Condition	Control	35-41 Days Exp to 1.5% CO ₂	9 Days Recovery on Air	4 Weeks Recovery on Air
Na, mEq/liter red cells	13.5	21.6 †	24.4 †	12.8
K, mEq/liter red cells	86.0	78.9 †	76.2 †	79.9
HCO ₃ , mM/liter red cells	14.3	17.0 †	17.0 †	16.3 †
CL, mEq/liter red cells	55.8	58.3	56.9	58.8

* Ten subjects.

† Statistically significant.

a. Erythrocyte Cation and Anion Exchange
in Chronic Respiratory Acidosis*

b. Dead Space and Arterial-Alveolar pCO₂
and pO₂ Gradient in Chronic Respiratory
Acidosis*

Condition	Control	40 Days Exp to 1.5% CO ₂	9 Day Recovery on Air	4 Weeks Recovery on Air
Physiological dead space	169	273 †	262 †	174
Physiological dead space % tidal volume	29 %	35 %	37.6 %	27 %
Anatomical dead space	157	214 †	213 †	163
Alveolar dead space	12	59 †	49 †	10
Alveolar pCO ₂ mmHg	38.2	39.6 †	39.9 †	37.4
Arterial pCO ₂ mmHg	39.4	44.9 †	43.9 †	38.3
Arterial-alveo- lar pCO ₂ mmHg	1.3	5.3 †	3.8 †	0.8
Arterial-alveo- lar pO ₂ mmHg	10.6	24.9 †	20.3 †	13.4

* Ten subjects.

† Statistically significant.

during the nine-day post exposure period. Normal values were reached after four weeks of recovery. Physio-chemical and perhaps temporary pathological changes in the lungs of the subjects might have contributed to these changes (231). Whether these changes increase the susceptibility of the exposed lungs to secondary infections or to effects of low level contaminants is an open question. The respiratory changes have been compared with changes found in emphysema patients, who usually have high CO₂ levels (231). A marked increase in physiological dead space has recently been found in submarine patrols - with CO₂ exposures averaging around 1.1% (219).

The venous plasma calcium mirrored the blood pH changes showing a decrease during the uncompensated phase of respiratory acidosis, a return to normal values during the compensated phase of respiratory acidosis and rose above control values during the 9-day post exposure period (233). These findings suggest that the long time period of adaptation and CO₂ retention (23 days) was related to the slow equilibration of the bone CO₂ store (mainly carbonate) with the elevated blood CO₂, which is supported by other findings in the literature. A plasma calcium tide, occurring 8 days post exposure, commensurate with increased CO₂ retention, indicated a release of the previously stored CO₂ from the bones.

It is known that increased urine pH and calcium levels do frequently result in urinary calculus formation. Since the urine pH was elevated above control values during the compensated phase of respiratory acidosis (24-42 days of exposure) and both the urine pH and urine calcium were higher than control values during the 9-day post exposure period, it is probable that chronic exposure to CO₂ could result in calculus formation in the urinary tract. This suggestion is supported by evidence from animal experiments. An increased incidence of kidney stone formation was found in rodents exposed to 1.5% CO₂ from 40 days to 90 days (222, 230).

Since it has been noted that urinary calculus is a rather frequent occurrence on submarine patrols, studies of calcium-phosphorus metabolism are presently being carried out on these vessels (219).

An increase in adrenal cortical activity was found during the 42 days of exposure to 1.5 percent CO₂ and the 9 day post-exposure study period (131). This response, mirrored by an increase in the ketosteroid output in the urine and a decrease in the absolute number of circulating eosinophils, was greater during the phase of compensated respiratory acidosis and post-exposure study period than early in the phase of uncompensated respiratory acidosis. It was also noted that the number of complaints showed a trend opposite to changes in adrenal cortical activity. The relative roles of confinement, anxiety, and chronic respiratory acidosis in producing the stress syndrome are not clear (42).

Cardiovascular capacity, as measured by various tests of cardiovascular function when the subjects were subjected to various work loads, decreased significantly throughout the exposure to 1.5 percent CO₂ and during the 9 day post-exposure study period. Although the subjects were undoubtedly carrying out less physical activity during the period of confinement, this reduction of circulatory reserve has been attributed mainly to CO₂ (224).

Subjects have been exposed to 3 percent CO₂ in air for periods of up to 144 hours (223, 226). The phase of uncompensated respiratory acidosis lasted only 2 to 3 days, indicating that renal mechanisms rather than bone CO₂ stores were primarily responsible for the return of blood pH to normal values (224). Subjective complaints, performance, and physiological findings suggest that the phases of uncompensated and compensated respiratory acidosis were associated with respective increases of sympathetic and parasympathetic nervous system tone. Increased "sympathetic tone" was characterized by significant increase above control values of resting pulse rate, neuromuscular excitability, responsiveness of the circulatory system to exercise and heat production after a cold load. The most undesirable clinical manifestations from breathing 3 percent CO₂ appeared during the "phase of increased parasympathetic tone," which was characterized by decrease of the above physiologic parameters to below control values. This phase continued for about 5 days into the post-exposure study period and could be maintained if subjects extended their exposure to 3 percent CO₂, but breathed this gas for only 8 hours daily. Chronic exposures of submarine crews to CO₂ levels in the range of 3 percent, showed that the concomitant lowering of the level of oxygen in the submarine atmospheres would not have been sufficient enough to have played a significant role in causing the effects noted above (225).

Another study with 3 percent CO₂ has more closely simulated possible chronic exposures to CO₂ in low pressure, oxygen enriched, space atmospheres (56). Eight normal individuals successively breathed, for periods of 4 days, atmospheres of air at 700 mm Hg; air at 700 mm Hg, containing CO₂ at 21 mm Hg; air at about 747 mm Hg; oxygen at 200 mm Hg; and oxygen at 200 mm Hg, containing CO₂ at 21 mm Hg. There was no difference in either the ventilatory response to CO₂ or the increase of the partial pressure of alveolar CO₂ produced by breathing CO₂ at these different ambient atmospheric pressures. The respiratory acidosis, as noted by changes in blood pH was essentially compensated in 3 days in each CO₂ exposure period. This blood pH change has also been observed in a recent study in which normal individuals breathed air at 700 mm Hg, containing CO₂ at 21 mm Hg for 5 days (94). These and other recorded physiologic parameters have clearly demonstrated that the partial pressure of inspired oxygen being the same, the response of man to CO₂ in a low pressure atmosphere is essentially the same as for an equivalent partial pressure of CO₂ at sea level pressure.

A chronic, compensated exposure to CO₂ may significantly alter an astronaut's physiological, and hence clinical tolerance to an acute CO₂ exposure, but few direct data are available on this issue. Electrolyte response curves in chronically exposed subjects are under study (97, 270). Also, the marked predisposition of patients suffering from emphysema and other hypoventilatory states to develop peptic ulceration has been well documented and could be a problem in space operations (42). Although an epidemiologic study has never been undertaken, peptic ulceration does not appear to have been a problem of World War II submarine crews who were exposed for weeks at a time to ambient CO₂ levels of up to 3.5 percent (219). Unfortunately, there can be marked species differences in CO₂ tolerance. Monkeys, for example, exposed to 3 percent CO₂ in air for 93 days, exhibit no demonstrable changes in any of the numerous physiologic parameters studied (242).

Behavioral Changes During Chronic CO₂ Exposure

No signs or symptoms which could be attributed directly to CO₂ appeared during or after the 42 day exposure of 21 normal individuals to 1.5 percent CO₂ (77, 221). This CO₂ level did not alter the performance of a number of tests of psychomotor function.

In contrast, chronic exposures to 3 percent CO₂ have usually produced a characteristic clinical picture. Various investigators have reported that for the first day breathing 3 percent CO₂, experimental subjects and submarine crews have manifested signs and symptoms of mild nervous system hyperactivity, such as increased motor activity, a feeling of excitement, euphoria, mental keenness and sleeplessness (23, 222, 226). During the second day, they often complained of headache. Of a greater significance, however, is a state of nervous system depression which set in at this time. This was characterized by a feeling of mental depression and cloudiness, the belief that memory and attentiveness were decreased, somnolence, mood alterations, and decreased appetite. Although this state improved somewhat after the third day of exposure, subjects never returned to normal during exposure. The somnolence has reportedly disappeared after 2 weeks exposure during submarine operations, but beyond this time, unexplained irrational ideas and bizarre behavior have usually appeared (222). The transition to air has often induced a temporary headache; it has taken 4 to 6 days until subjects felt completely well again.

Results of psychomotor tests have shown improvement during the first day of exposure to 3 percent CO₂; but thereafter and for several days into the post-exposure period, a significant impairment in performance (221, 223). Most individuals were aware of increased breathing at the 3 percent CO₂ level, particularly when performing light physical work or when fatigued. This symptom reportedly disappears after 2 to 3 days of exposure (94). The capacity to do physical work which would probably be initially limited at this CO₂ level, as in acute exposures, but may also improve with time. From an operational standpoint, it would also be important to know the effect this level of CO₂ has on fatigability and on recovery after strenuous activity.

It is important to note that the above studies of CO₂ on performance have never definitely ruled out the contribution of confinement to the production of signs and symptoms attributed to CO₂ toxicity. A recent, comprehensive review of confinement cites many confinement studies which were characterized by clinical manifestations identical to and occurring often in the same sequence after individuals were confined as those reported from chronic exposure to CO₂ (87).

The treatment of the clinical manifestations resulting from a chronic exposure to an elevated inspired CO₂ level has not been covered in the literature. As was discussed under "Acute CO₂ Toxicity," there are at the present time no practical specific therapeutic measures for treatment of the CO₂-induced acidosis in space (42). A suitable oral analgesic might alleviate the headache which can manifest initially on exposure to CO₂. Successful use might also be made of an orally administered tranquilizing agent, such as reserpine or chlorpromazine, which might control the alterations in sympatho-adrenal activity that apparently cause the sleeplessness and excitement in the early stages of CO₂ toxicity. It is also possible that an oral central nervous

system stimulant, such as dextroamphetamine or methylphenidate, might combat the state of depression which can apparently occur after compensation to CO₂. An amphetamine might also be proven successful for decreasing the fatigability associated with CO₂ exposure. More work is needed in this area.

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11. INERT GAS

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INERT GAS

Addition of inert diluent gas to a space cabin atmosphere alters several engineering and physiological variables which must be considered. Table 11-1 gives the physical properties of the different inert gases.

Decompression Sickness - The most significant physiological alteration determined by the inert gas environment is decompression sickness. This factor is covered in Pressure, (No. 12).

Tables 11-2, 11-3 and Figure 11-4 give some of the bio-chemical properties of the inert gases which can be used in predicting the frequency or decompression symptoms after different inert gas exposures (5, 89).

Thermal Factors

Tables 6-18 to 6-69 present the significant thermodynamic properties of the individual gases and gas mixtures of several candidate atmospheres for space cabin use (90). Figure 11-5 may be used to determine the thermal conductivity of other oxygen-inert gas mixtures. Alterations in control of body temperature, in thermal comfort zones, and in design of cabins and space suits brought about by the different inert gas environments have been covered in Thermal, (No. 6), pages 6-18 to 6-69.

Table 11-1

Physical Properties of Inert Gas

(After Roth⁽⁸⁹⁾)

Property	Gas					
	He	Ne	A	Kr	Xe	N ₂
Atomic number.....	2	10	18	36	54	7
Molecular weight.....	4.00	20.18	39.94	83.80	131.30	28.00
Color	Colorless					
Density, gm/liter, at 0° C and 1 atm.....	0.1784	0.9004	1.784	3.708	5.851	1.251
Heat capacity (C _p) at 25° C and 1 atm, cal/°C-gm-mole.....	4.97	4.97	4.97	4.97	4.97	6.96
Specific heat ratio at 0 to 20° C, C _p /C _v	1.63	1.64	1.67	1.69	1.67	1.404
Sound velocity at 0° C and 1 atm, m/sec.....	970	435	319	213	168	337
Acoustic impedance at 0° C and 1 atm, dyne-sec/cm ²	17.3	38.5	56.9			42.1
Thermal conductivity at 0° C and 1 atm, cal/°C-cm-sec	34.0 × 10 ⁻⁸	11.04 × 10 ⁻⁸	3.92 × 10 ⁻⁸	2.09 × 10 ⁻⁸	1.21 × 10 ⁻⁸	5.66 × 10 ⁻⁸
Viscosity at 20° C and 1 atm, micropoise.....	194.1	311.1	221.7	249.6	226.4	175.0
Critical properties:						
Density, gm/cm ³	0.069	0.484	0.531	0.908	1.105	0.3110
Pressure, atm.....	2.26	26.9	48.0	54.3	58.0	33.54
Temperature, °C.....	-267.9	-228.7	-122.44	-63.8	16.59	-146.9

Specific references for each property are available⁽⁸⁹⁾.

Table 11-2

Biochemical Properties of Inert Gases

(Numbers in parentheses were calculated by Graham's law from nitrogen data)

(After Roth⁽⁸⁹⁾)

Property	Gas					
	He	Ne	A	Kr	Xe	N ₂
Bunsen solubility coefficient in water at 38° C....	0.0086	0.0097	0.026	0.045	0.085	0.013
Bunsen solubility coefficient in olive oil at 38° C.....	0.015	0.019	0.14	0.43	1.7	0.061
Bunsen solubility coefficient in human fat at 37° C.....		0.020		0.41	1.6	0.062
Oil-water solubility ratio.....	1.7	2.1	5.3	9.6	20.0	5.1
Relative diffusion through gelatin at 23° C.....	1.0	(0.42)	0.30	0.21	0.13	0.36
Diffusion constants through liquids at 37° C, cm ² /sec × 10 ⁻⁴ :						
Olive oil.....	(18.6)	(8.34)	(5.92)	(4.10)	(3.27)	7.04
Lard.....	(9.28)	(4.15)	(2.94)	(2.08)	(1.62)	3.50
Serum.....	(57.6)	(25.7)	(18.2)	(12.6)	(10.1)	21.7
Agar gel.....	*44.4					
Water.....	(71.3)	(32.0)	(22.7)	(15.8)	(12.6)	27.0
	(79.2)	(34.8)	(25.2)	(17.5)	(13.9)	30.1
	63.2					

^a Calculated from data of Ref.(38).

References for specific data points are available (89).

Table 11-3

Solubility of Nitrogen in the Blood Component

(After Van Slyke et al⁽¹⁰⁸⁾)

Component	Bunsen coefficient of nitrogen
Normal blood.....	0.0130
Normal plasma.....	.0117
Red cells.....	.0146
Water.....	.0127

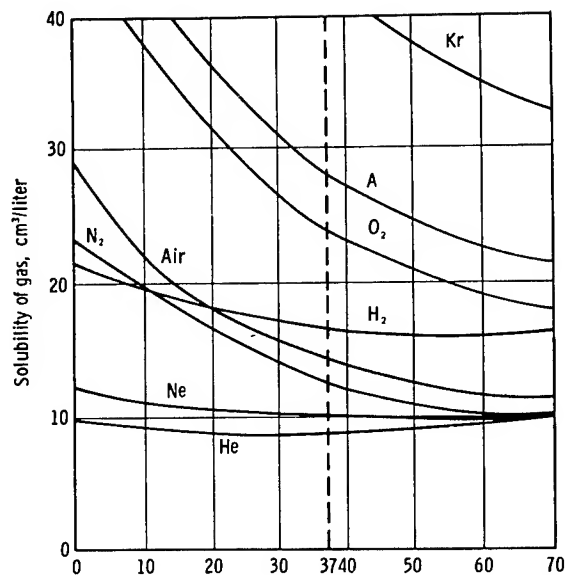


Figure 11-4

Solubility of Gases in Water at Different Temperatures

(After Tietze⁽¹⁰¹⁾)

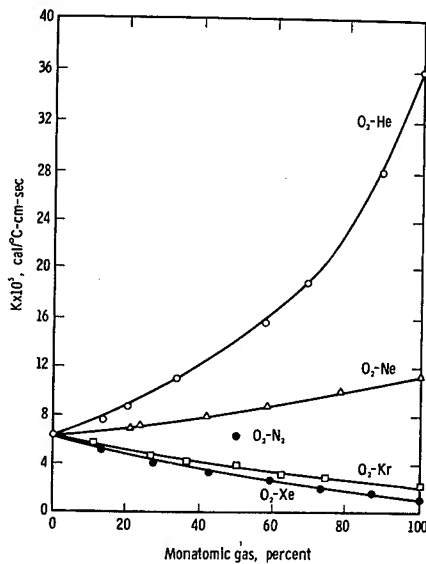


Figure 11-5

Thermal Conductivity of O₂-He, O₂-Ne,
O₂-Kr, and O₂-Xe Mixtures at 30°C

(After Srivastava and Barua⁽⁹⁶⁾)

The temperature selected as most comfortable in several different gaseous environments is recorded in Table 6-42. No wind speed is recorded in these studies but the levels were those below the speed for rustling of paper. Uncertainties regarding comfort zones in helium-oxygen mixtures are discussed with reference to this table.

Psychrometric charts for different oxygen and oxygen-inert gas mixtures are presented in Figures 11-6 and 11-7.

Vocal Factors

Alteration of the voice by inert gas factors has been reviewed (51, 61, 89, 93). Changes in frequency can be predicted by assuming that the oronasal passages are a vibrating air column and the frequency of the sound produced by a vibrating air column is proportional to the velocity of gas/wavelength of sound. The velocity of sound, in any "perfect" gas mixture can be obtained by the equation: (102)

$$V_{\text{sound}} = \sqrt{\frac{(\gamma p)}{d}} = \sqrt{\frac{\gamma R T}{M W}} \quad (1)$$

where T = absolute temperature

γ = ratios of specific heat

p = equilibrium pressure

γp = adiabatic bulk modulus

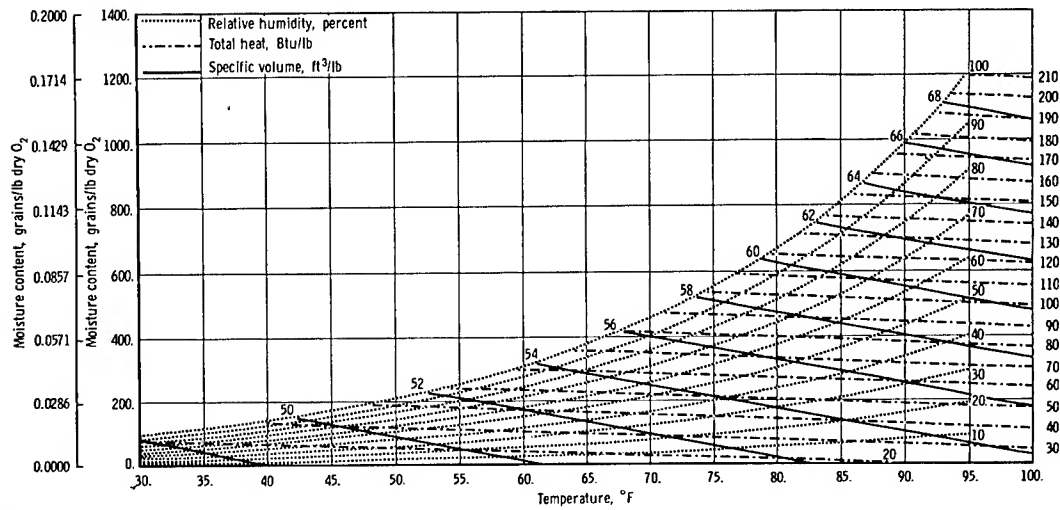
d = equilibrium density

R = universal gas constant

MW = molecular weight

Table 11-6
Psychrometric Chart for Oxygen
(After Green⁽⁴¹⁾)

a. 3.5 psia (180 mm Hg)



b. 5.0 psia (258 mm Hg)

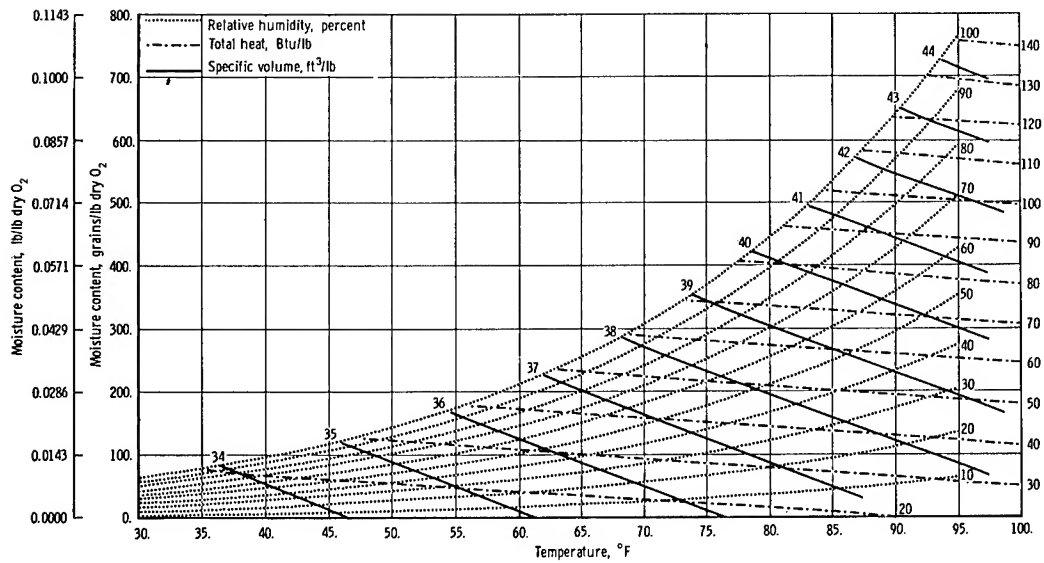


Table 11-6 (continued)

c. 5.0 to 10.0 psia (258 to 517 mm Hg)

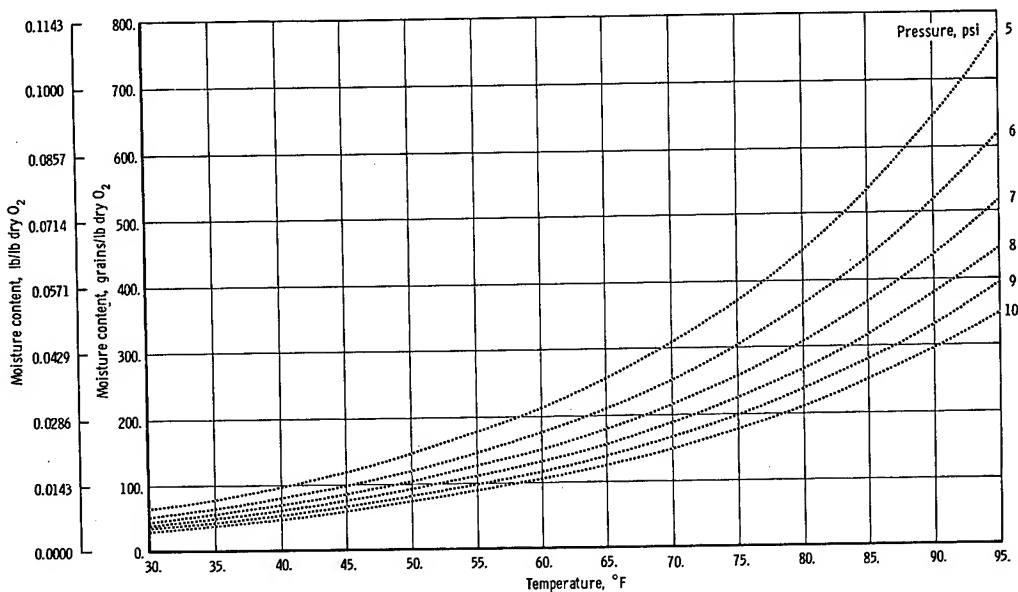


Table 11-7

Psychrometric Chart for Mixed Gases
(After Green⁽⁴¹⁾)

a. Air at Sea Level (14.7 psia)

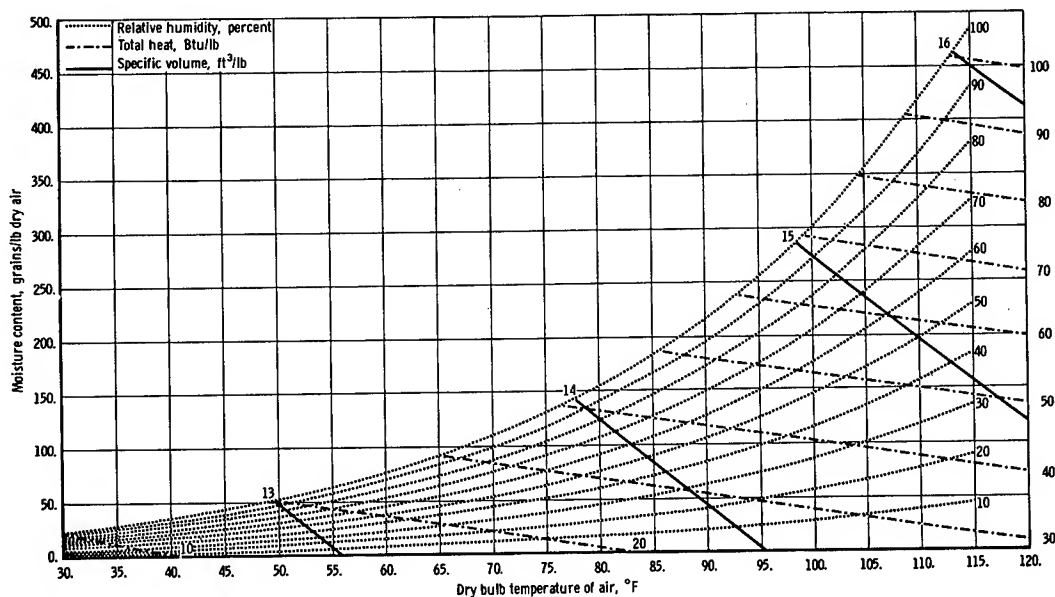
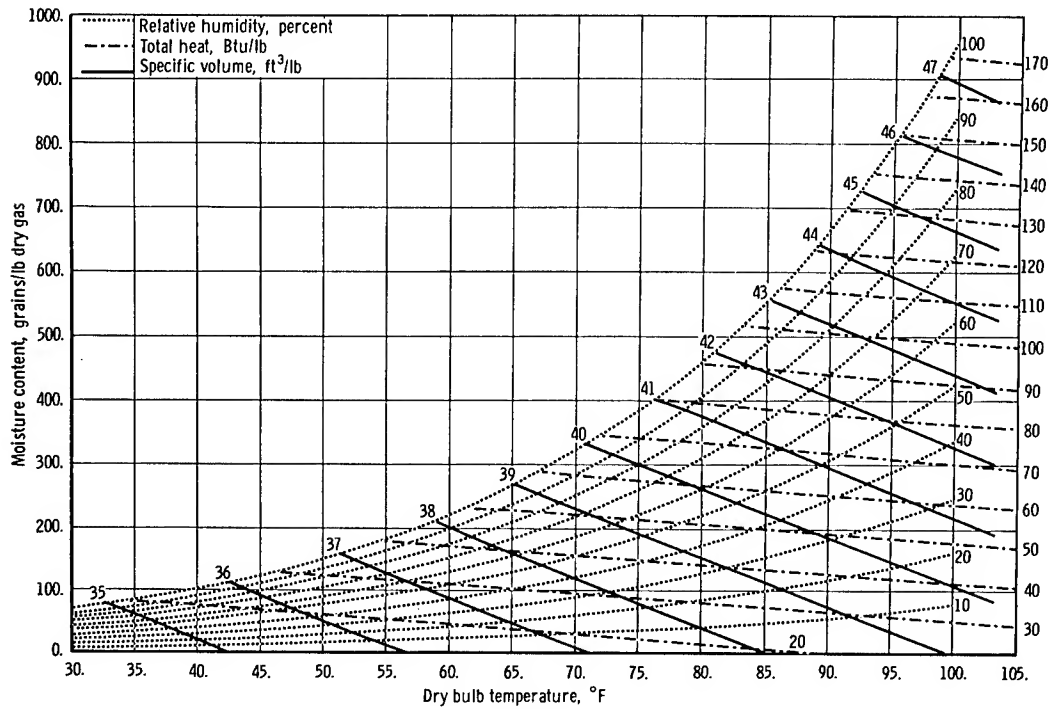


Table 11-7 (continued)

- b. 70 Percent Oxygen at 3.5 psia (180 mm Hg) and
30 Percent Nitrogen at 1.5 psia (77 mm Hg)



- c. 50 Percent Oxygen at 3.5 psia (180 mm Hg) and
50 Percent Nitrogen at 3.5 psia (180 mm Hg)

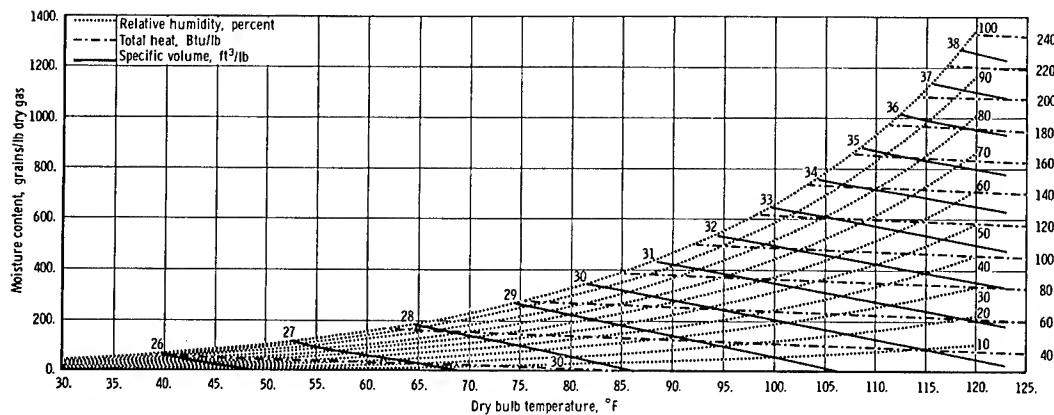
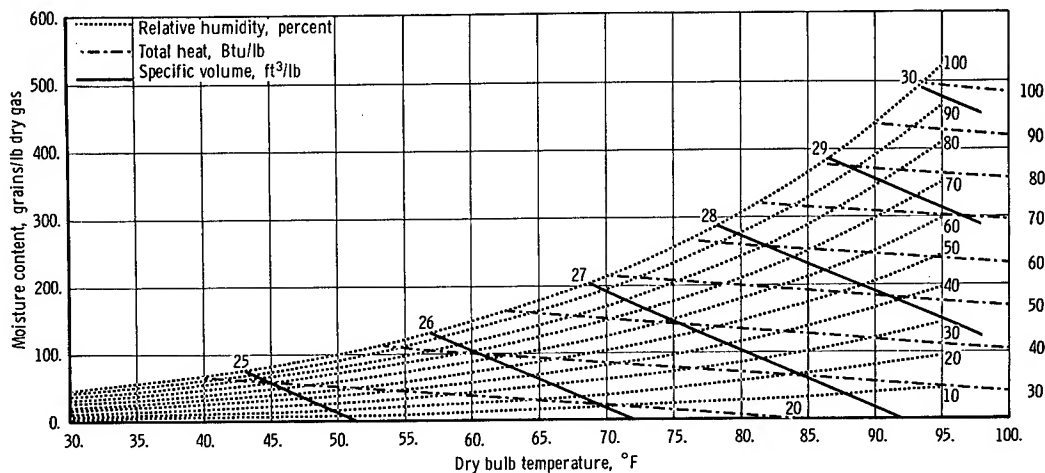
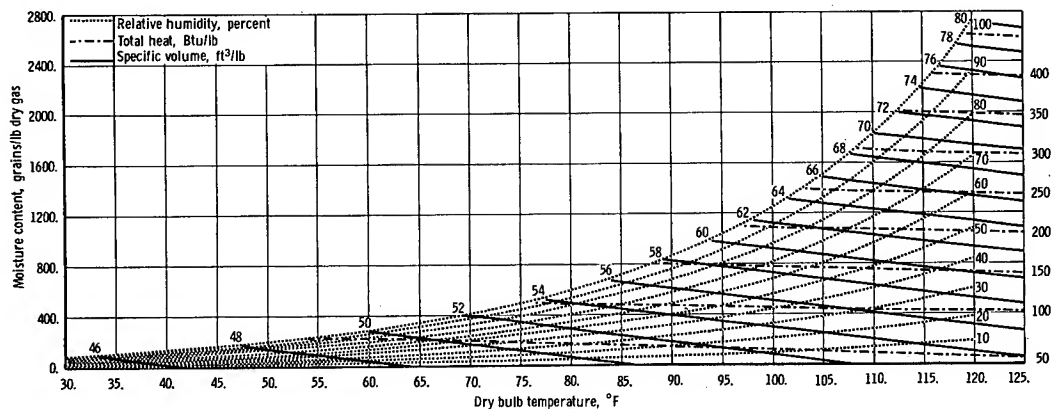


Table 11-7 (continued)

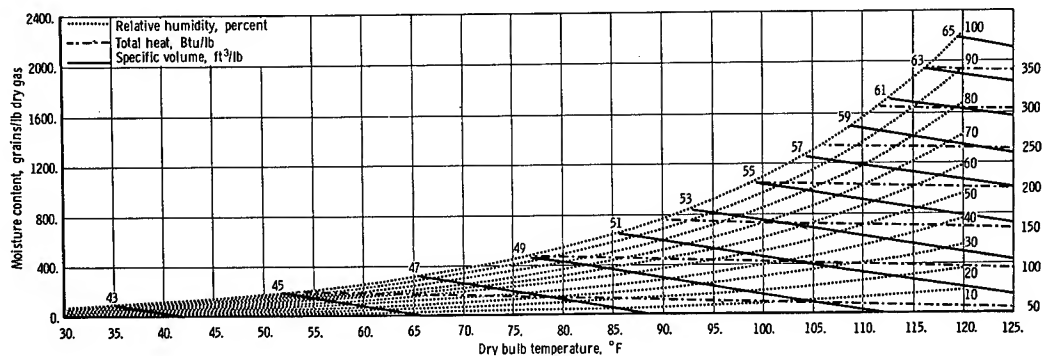
- d. 47 Percent Oxygen at 3.5 psia (180 mm Hg) and
53 Percent Nitrogen at 3.9 psia (200 mm Hg)



- e. 70 Percent Oxygen at 3.5 psia (180 mm Hg) and
30 Percent Helium at 1.5 psia (77 mm Hg)



- f. 50 Percent Oxygen at 3.5 psia (180 mm Hg) and
50 Percent Helium at 3.5 psia (180 mm Hg)



Experimentally, this prediction of changes in frequency is altered by the audio-vocal feedback system which modifies the frequency of the vocal cords in response to the abnormal audible frequency. The resonant systems of the human are also not ideal resonating columns. Several reviews of the mechanics of phonation should be consulted for a more detailed analysis of the second-order factors in speech propagation which require further study in unusual atmospheres (16, 32, 78, 106, 110).

The low pressure and low percentage helium which can be used in a space cabin dilutes out the inert gas effect. Recent studies suggest that such helium-oxygen mixtures at low pressures create so little distortion of speech and noise as to cause no major problem in a space cabin (23, 24, 25, 74). In 56% He - 44% oxygen at 7.4 psia, there is slightly reduced intelligibility in the presence of noise. There is an increase in the mean second formant frequency of 1.35 times above that in air at S. L. In 80% He - 20% oxygen at sea level pressure this is increased to 1.6 times that of air (74). In Soviet studies at sea level pressure and 80% He - 20% oxygen, there is an increase of frequency by about 0.7 octave (30, 92). Intelligibility can be improved by simple filtering (92) and by vocoder techniques (40).

More detailed studies of voice changes, loud-speaker characteristics, and receiver or hearing patterns are under way (95).

Metabolic Factors

Alteration of the normal ratio of oxygen to inert gas for long periods of time has been thought to be of potential detriment to the human. Table 11-8 reviews all human experiments performed over periods of days in atmospheres proposed for space cabins. Similar charts for animal experiments are available (86). Oxygen toxicity is covered in Oxygen-CO₂-Energy, (No. 10).

Studies of human exposure to helium are summarized in blocks 19 to 24 of Table 11-8 (113). Slight increase in oxygen consumption is attributable to compensation for the cooling effects produced by He and by increased evaporation resulting from the low pressure. Minor changes in plasma electrolytes, BUN, and catecholamines were accounted for by dietary changes and exercise stress. The single study on exposure of animals to neon-oxygen mixtures at atmospheric pressure suggests that unknown toxic factors in the mixtures and poor controls may have been responsible for the equivocal results obtained (119). There are no data available on the effects of chronic exposure of humans to neon-oxygen mixtures.

There are suggestions in the literature that helium may alter metabolic pathways in some biological systems (2, 13, 22, 50, 89, 117, 118). The significance of these findings to human exposure is yet to be elucidated, especially the role of nitrogen gas in normal metabolism. They may, in some way, be related to inert gas narcosis.

The pathological physiology of inert gas narcosis has been recently reviewed in great detail (10, 35, 81, 86, 89). The many hypotheses regarding the mechanism of anesthesia brought about by xenon at one

Table 11-8

Summary of Experiments in Space-Cabin Atmospheres*

Humans

(After Roth (86))

Atmosphere*	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
1. P_{O_2} 190-210 P_{N_2} 20-40 2 subjects	65 to 72 hrs	None			Appeared safe in contrast to P_{O_2} of 578 mm Hg where bronchitis, fever and pareses-thesias were noted.	Becker-Freysung and Clamann (6, 7), 1942, 1950
2. P_{O_2} 380 10 subjects	24 hrs in full pressure suit	None			No symptoms of tracheo- bronchitis as seen at P_{O_2} of 570 mm Hg.	Comroe (20), 1945
3. P_{O_2} 181 (100%) 2 subjects	3 days and 5 days in full pressure suit	Irritation of eye, nose and throat.	Normal pulmonary function tests, hematology, urinalyses and blood chemistries; decreased eosinophiles and elevated 17 Keto-steroids attributed to "stress" of the suit.	Pustular dermatitis from poor suit hygiene.	Irritation probably due to dryness.	Hall and Martin (43), and Hall and Kelley (42), 1960, 1962
4. P_{O_2} -418 P_{N_2} -105 (oxygen peaked transiently to 225 mm Hg) 6 subjects	7 days	Substernal tightness on deep inspiration on days 2-7; intermittent aural atelectasis; symptoms disappeared within 24 hrs after exposure terminated.	Slight decrease in vital capacity in 2 subjects; x-ray suggesting patch of atelectasis in one subject. Hemograms and urinalysis are normal.	Dermatitis due to poor clothing hygiene.	Aural and pulmonary atelectasis due to lack of nitrogen-brake effect.	Michel et al (68), 1960
5. P_{O_2} -150-160 P_{N_2} -220-230 5 subjects	7 days	None	Normal			Steinkamp et al (98), 1959

* All pressures in mm Hg

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
6. pO_2 -150 PN_2 -230 2 subjects	30 days	None	Cardiovascular changes as in # 7. No other findings.		See # 7. Unpublished data on 3 other subjects show similar findings (111).	Welch et al (112), Morgan et al (71), 1961, 1961
7. pO_2 -176 PN_2 -5% contamina- tion 2 subjects	17 days	Dryness of nose and respiratory tract, eye irritation, nasal congestion for 72 hrs, then decreased as humidity rose; occasional paresthesia of calves and arms; aural atelectasis; retrosternal pain in one subject, decreased by pressure elevation.	Vital capacity decreased by 10 % at 5 days, no x-ray findings; decrease in diastolic pressure in several subjects; decreased exercise tolerance, normal orthostatic tolerance, transient abnormal EKG findings on exercise test, decrease in total body water, blood volume and plasma volume; no hemoglobin changes.		Fluid and cardiovascular defects probably due to inactivity and evaporative water loss.	Welch et al (112), Morgan et al (71), 1961, 1961

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres
HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Pathology	Comments	Reference
<p>PO_2</p> <p>a) 380</p> <p>b) 258</p> <p>c) 196</p> <p>$\text{N}_2 < 0.5\%$</p>	14 days	Weight loss; loss of appetite; occasional bends symptoms; cough on vital capacity testing; aural atelectasis; head colds and sore throats in some subjects; eye irritation; substernal discomfort; aerotitis in several subjects, coughing after MBC tests.	<p>β-strep in throats; occult blood in stool of 1 subject; decreased mean oxygen content in 380 mm Hg suggesting abnormal hemoglobin; progressive decrease in MBC in 196 group; normal vital capacity; elevated OH steroids in 258 group; normal blood electrolytes, glucose and BUN; lack of strict anaerobic bacteria in skin; protein and casts in urine in 380 and 258 groups. Hemoglobin decreased by about 2 gm %; increased osmotic fragility, slight increase in reticulocytes; rbc microcytic, anisocytotic, occasionally spherocytic, polychromatic, normoblasts, hemoglobin-stippled, Heinz bodies, Howell-Jolly bodies, Cabot ring cells, flat Price-Jones curves; vacuolization of white blood cells; post exposure reticulocytosis.</p>		<p>Tricresyl phosphate, toluene disocyanate and mercury vapor were possible contaminants in cabin.</p> <p>Oxidative hemolytic anemia present, renal changes unexplained.</p> <p>One subject with thalassemia had drop of 5 Gm % in hemoglobin.</p>	Helvey (46), 1962
21 subjects						
<p>Total pressure</p> <p>192 \pm 15</p> <p>pO_2 - 174 \pm 15</p>	17 days continuous	Same as #7, plus symptoms of depression in several subjects; one case of joint pain may have not been dysbaric. Crepitant rales at posterior lower lung fields in six subjects.	Same as #7, plus arterial oxygen unsaturation in 2 or 3 of the subjects as low as 90%.		2 of these subjects reported in #7; same comments as #7; arterial unsaturation possibly caused by A-V shunting of atelectasis.	Morgan et al (70), 1963
8 subjects						

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres
HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
P ₁₀₁ -388 P _{O₂} -199 P _{N₂} -199	30 days	Normal performance except for difficulty in sleeping due to noise and the expected social stress of small groups.	Slight decrease in hemotocrit (-5%) and in red cell mass (-7%) during test (?blood letting); BUN's slightly elevated with no explanation given; increased water loss via skin and respiratory tract (low pressure); no change in renal function by G.F.R., CPAH' Cosm', and output of Na,K and Cl. Catecholamine outputs reflect social and emotional stress; decrease in pulse rate response to exercise in latter part of test reflecting insufficient programmed exercise during experiment. Early mild decrease in vital capacity and timed vital capacity for first 4 days returned almost to normal; MBC - normal altitude response. Spread of hemolytic Staph. aureas from one subject to two others.	Subjects were generally within normal clinical limits of well being.	General Electric (37), 1964.
4 subjects					
P _{O₂} -258	2 weeks (acceleration profiles before and after exposure).	Serous otitis media in several subjects, cleared with decongestants and valsalva maneuvers.	Decrease in scotopic peripheral vision. Subsequent study of dark adaptation (27) showed minimal decrease at this pressure of O ₂ associated with increased age of subjects. Normal pulmonary mechanics and diffusion capacity; hemogram normal except for effects of blood letting, urinalysis same as controls; normal EEG and EKG; blood chemistries normal.	Cabin fire terminated study.	Hendler (47), 1963, Mammen et al (62), 1963, Critz et al (27), 1964.
3 subjects completed profile					

Table 11-8 (continued)

Table 11-8 Summary of Experiments in Space-Cabin Atmospheres				
HUMANS (continued)				
Atmosphere	Duration	Symptoms	Laboratory Findings	Comments
a. P_{O_2} 258 $P_{N_2} ? < .25\%$ (8) (6) aborts	72 hrs	a. 6 subjects aborted at < 25 hrs because of bends pain or dyspnea. Of the remainder 2/8 substernal discomfort, 3/8 bends pain, 3/8 earache, 2/8 conjunctival irritation, 1/8 GI upset, 1/8 occipital headache.	a. 1/8 had decrease in vital capacity of > 1600 cc with x-ray signs of atelectasis in both bases; no hemolysis; normal hemoglobin, red cell volume, serum bilirubin; normal rbc glu-6 P. Dase and serum isocitric dehydrogenase. Normal LDH, normal serum glucose and lipase; normal NAD, NADP, NADPH; hyperlipemia with lactescent serum and alteration of the α/β fraction of serum lipoproteins (6 hrs after meals); vision normal (see b).	Study was primarily for vision; no causes for isocitric dehydrogenase or hyperlipemic changes are evident.
b. P_{O_3} 380 $P_{N_2} ? < .25\%$ (6)	72 hrs	b. 1/6 bilateral earaches on descent to sea level; 1/6 wheezing in chest on return to sea level; 1/6 pain in lower left chest partly relieved by antacids; 1/6 nasal congestion.	b. 1/6 had 1700 cc decrease in vital capacity with bilateral plate-like atelectasis at both bases; other tests same as a but 2 subjects had elevated isocitric dehydrogenase of unknown cause (both subjects older and of moderate alcohol intake); hyperlipemia as in (a). Visual (a and b) - normal dark adaptation, visual acuity, color discrimination, stereopsis, vertical and lateral phorias, C.F.F., retinal perimetry electroretinography and intraocular tension; diameter of retinal arteries decreased by 19% and of retinal veins, by 25%.	
14 subjects				

Reference
Critz et al (27), 1964,
Hendler (48), 1966,
DuBois et al (31),
1966, Gallagher et al
(36), 1965, Nobrega
et al (75), 1965.

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres
HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
13. P_{tot} -259 PO_2 -243 PN_2 -5 4 subjects	14 days continuous	Similar to #14. Erythema of pharynx and crepitant rales at bases clearing with deep breathing and substernal pain.	EKG-marked sinus arrhythmia with palpitations in one subject, hemogram and urinalysis normal, minimal elevation in catecholamines pre- and during experiment. Arterial PO_2 , A-V shunt estimate, chest x-ray, vital capacity show no evidence of significant atelectasis.	Effect of O_2 on mucous membrane and aural atelectasis are the most significant findings.	Morgan et al (70), 1963
14. P_t -258 PO_2 -254 PN_2 -0.5 4 subjects	30 days continuous	Weight stable, nasal congestion (4/4); aural atelectasis (4/4); cracked lips; trapped intestinal gas (2/4); burning of eyes (1/4); paresis (1/4); rash (1/4); crepitant rales in bases of lung (2/4).	35% decrease in work capacity on Balke test after 30 days; normal dark adaptation; urinalysis and creatinine clearance is normal; decreased forced vital capacity (-5%); increased M. B. C. (+50%); normal oxygen-carrying capacity and saturation; normal diffusion capacity and residual volumes of lungs; oxygen consumption is normal. Hematocrit reduced by 9.1% (control dropped 3.4%); normal reticulocytes, osmotic fragility, glutathione, rbc glucose-6-PDase, serum bilirubin; $T_{1/2}$ of Cr^{51} studies were normal.	No active hemolysis evident; pulmonary and aural atelectasis present; trapped gas in GI tract discomforting. Decrease in work capacity due to exercise restriction.	Herlocher et al (49), 1964, Robertson et al (82), 1964, Zalusky et al (120), 1964.
15. Same as #14 4 subjects	Same as #14	Similar to #14	Similar to #14	Data unpublished	Welch (111), 1966

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
<p>16. P_{O_2}-258 No % N_2 stated as contaminant</p> <p>6 subjects</p>	20 days continuous in ventil- ated pres- sure suits	Symptoms related to suit problems with flaking of skin, discomfort in sleeping, tem- perature and humidity control; minor psychological factors related to small group stress.	No significant changes in hemograms, Price-Jones indices; normal osmot- ic fragility and mechanical fragilities and bilirubin (direct and indirect); normal reticulocytes. All pulmonary function tests normal except for slight decrease in vital capacity; no atelec- tasis by x-ray; normal urinalyses; no hemoglobin type A ₂ or F; normal ser- um electrophoretic lipoprotein frac- tions; normal serum isocitrate dehy- drogenase; normal serum haptoglobin, haptoglobin-bound hemoglobin, rbc glucose-6-P-Dase. 6-8% decrease in diameter of retinal arteries and veins.		Kellett and Coburn (57), 1966, Coburn (18), 1966.
<p>17. P_{tot}-700 P_{O_2}-233 P_{N_2}-436</p> <p>4 subjects</p>	30 days continuous	Weight stable. No complaints.	36% decrease in work capacity on Balke test after 30 days; normal dark adaptation and ophthalmoscopy; normal vital capacity, MBC, diffusion capacity, residual volume, and O_2 consump- tion. Hematocrit decreased 6.7% (controls dropped 3.4%); other blood studies normal as in #14.	Decrease in work capacity probably due to exercise restriction. De- creased hemato- crit is partly due to blood withdrawal and exercise restric- tion.	Herlocher et al (49), 1964, Robertson et al (82), 1964, (120) Zalusky et al 1964.
<p>18. P_{tot}-380 P_{O_2}-160 P_{N_2}-160 with decompres- sion to P_{tot} 190</p> <p>12 subjects</p>	24 hr maxi- mum. Com- plex proto- col	Subjects experienced sym- ptoms of dysbarism at some time in the study.		Study related only to decompression sick- ness. Standard exer- cise was 10 step-ups on a 9 inch platform every 5 minutes for 3 hrs. Subjects ap- pear to be of a high- risk group (80).	Hendler (48), 1966, Damato (28), 1963

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres
HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
<p>19. P_{tot}-760 PO_2-171 pHe-578 N_2-1.5% 4 subjects</p>	<p>10 hrs (1) 25 hr (1) 8 hrs (suit)(1) 24 hrs (suit)(1)</p>	<p>Chilliness at 18-24°C (65 to 75°F)</p>	<p>Lower skin temperatures than at air equivalent; reduction in thermal comfort zone of 3°C in cabin; higher gaseous temperature required in suit for comfort; less sweat loss at high temperatures in suit. Speech shifted to higher frequency by 0.70 octave with slight decrease in intelligibility. Normal auditory function.</p>	<p>Nervous, cardiovascular and respiratory changes were all attributed to hypodynamic environment and isolation rather than to the helium per se.</p>	<p>Dianov (29), (59), Kuznetsov 1964, 1964.</p>
<p>20. Equilibration with P_{tot}-380 PO_2-160 pHe-160 Complex protocol. 12 subjects</p>	<p>6 to 12 hrs; mild exercise at 35,000 ft.</p>	<p>Subjects experienced dysbarism (see original protocol).</p>		<p>Study of bends incidence after helium-oxygen equilibration. Residual tissue nitrogen appeared to combine with helium in early stages of equilibration to give joint discomfort at 18,000 ft and frank bends at 35,000 ft.</p>	<p>Kellett et al (58) 1966.</p>
<p>21. P_{tot}-380 PO_2-165 pHe-206 exercise at 100 watt work load for 1 hr every 4 days</p>	<p>15 days continuous</p>	<p>4/4 conjunctivitis which cleared when humidity was increased; 1/4 acute prostatitis.</p>	<p>Intermittent proteinuria in concentrated morning specimen with normal BUN, serum creatinine and creatinine clearance. Hemogram, clotting tests, liver function tests, rbc glucose 6-P Dase, and serum electrolytes were normal. Reduced treadmill time on Balke test of 1-5 minutes at 15 days. One subject had syncope with EKG changes of bradycardia and transient nodal rhythm during post exercise.</p>	<p>Prostatitis probably unrelated to atmosphere. Deconditioning from confinement of 35 days during total experimental protocol. Pulmonary changes due to low pressure, density, and flow resistance of atmosphere.</p>	<p>Zeft et al (121), 1966. Robertson et al (83), 1966, Epperson et al (33), 1966</p>

Table 11-8 (continued)

Table 11-8
Summary of Experiments in Space-Cabin Atmospheres

HUMANS (continued)

Atmosphere	Duration	Symptoms	Laboratory Findings	Comments	Reference
4 subjects					
P_{tot} 258 363 PO_2 181 170 170 P_{He} 72 185 185 or P_{N_2} 70 man flight:	Up to 4 hrs equilibration in a complex protocol; unsteady state gas condition	Bends symptoms after both P_{He} and P_{N_2} exposure (see text).	perimert tilt table orthostasis. Normal BMR; 44% increase in MBC as expected from low density of air and reduction of flow resistance; forced vital capacity decreased by 5% after ascent and returned after descent. Lung volumes and carbon monoxide diffusion capabilities normal. Skin temperatures are lower after exercise than at sea level conditions as expected from thermodynamic considerations (33, 83, 89).	Study compared bends incidence after O_2 - N_2 vs O_2 -He mixtures. Unsteady state gaseous conditions limit extrapolation to equilibrium conditions	Beard et al (5), 1966, Beard et al, (5), 1967.
P_{tot} -258 PO_2 -175 P_{He} -74 23. P_{N_2} - 2	56 days with exercise regimen	Dryness of mucous membranes (4/4); nasal congestion (2/4); conjunctivitis (3/4); increased flatus (4/4); abdominal pain from trapped intestinal gas (2/4) parasthesias with exercise (3/4); middle ear problems (0); decompression disturbances (0).	Renal studies - normal inulin, PAH, endogenous creatinine clearances, concentrating and dilution tests, 24 hr protein excretion, blood pH and bicarbonate and other electrolytes. Blood enzymes -normal glutamic dehydrogenase, no lipase; 14% decrease in LDH and slight decrease in heart isozyme; slight increase post experiment in gluc 6-P-Dase, glutathione and	Humidity problems recurred with irritation of mucous membranes. Flatal problems bothersome; no oxidative hemolysis seen; enzyme changes not significant except for unexplained SGOT and SGPT rise, no ob	Adams et al (1), Bartek et al (4), Cordaro et al (26), Glatte et al (39), Hargreaves et al (44), Heidelbaugh et al (45), Moyer et al (72), Rodgin et al (85),

(continued)

Table 11-8 (continued)

Summary of Experiments in Space-Cabin Atmospheres				
HUMANS (continued)				
Atmosphere	Duration	Symptoms	Laboratory Findings	Comments
			<p>glutathione stability associated with a 3.4% decrease in hematocrit in the post experiment period; mild elevation in SGOT and SGPT (1/4) with normal liver function. No orthostatic intolerance as seen in previous studies.</p> <p>Respiratory - basal O_2 and CO_2 exchange were increased (evaporative factors), vital capacity transiently lowered by 4% on ascent; slight decreased expiratory reserve volume at altitude, normal residual volume, MBC increased by 40% (decreased density) normal CO_2 diffusion capacities.</p> <p>Nutrition - high fecal fat (high M. P. fat coating bite-sized food) and poor energy utilization of experimental diet (88%); excessive flatus (beverages and ?fat); distension of abdomen caused pain; decrease in enterococci in stools.</p> <p>Bacterial - transfer of staphylococci between crew.</p> <p>ECG - one subject had intermittent Wolf-Parkinson-White syndrome.</p> <p>X-ray - mucous membrane thickening in sinuses (1/4).</p>	vious toxic contaminants in atmosphere.
				Robertson et al (83), Ulvedal et al (104), Vanderveen et al (107), Zeft et al (123), Zeft et al (122), 1966.
4 subjects				
P_{tot} -360	30 days	See Thermal Environment (No. 6).	See Thermal Environment (No. 6).	Primarily equipment and thermal study; crew performance normal.
PO_2 -180				
24. P_{N_2} -180				
P_{tot} -250	5 days	Same	Same	
PO_2 -180				
pHe-70 4 subjects				Bonura and Nelson (12), Secord and Bonura (94), 1967, 1965.

atmosphere and other inert gases at higher pressure invoke clathrate and hydrate formation or protein binding concepts. Abnormal metabolic factors which may arise in more prolonged exposure to He in space cabin atmospheres could have a basis in these biophysical areas. Extension of human exposure to helium-oxygen beyond 56 days (block 23 in Table 11-8) in spacecraft should probably be preceded by day-for-day simulation on the ground. Less stringent ground-based simulation will be required for oxygen-nitrogen mixtures. Criteria for selection of space cabin atmospheres will be presented below. (See Table 11-16.)

Leakage of Gas from Cabin

Slow leakage of gas in long space missions may lead to a condition in which the total pressure in the cabin must be reduced to minimize leakage so that the mission can be completed. Slow leakage will also require a specific weight penalty for make-up oxygen and inert gas. More rapid leakage after penetration of the cabin by meteoroids or after accidental puncture will lead to acute hypoxia as the limiting factor. (See Pressure, No. 12.)

Major leakage from space cabins appears to arise from elastomer-to-metal hatch seals. This must be accounted for in compensatory gas storage. The mass rate of leakage is dependent on the molecular composition of the gas (11, 12, 64, 90). Selection of appropriate equations for the description of slow leaks through elastomer-metal seals has been a problem. The most divergent equations for seal-leak calculations are those for isentropic sonic-orifice flow used in the case of large holes and those for capillary, free-molecular flow. Mason's recent modification of the Knudsen equation for capillary flow of laminar continuum to free molecular transition at a final pressure of zero appears to be accepted as a reasonable approach: (64)

$$q = \frac{5.22 D^4 P'^{1/2}}{10^6 \mu' L} + \frac{7.42 D^3 P'}{10^6 L} \sqrt{\frac{T'}{M'}} + \left[\frac{7.44 D^2 \mu' T'}{10^6 M' L} \right] \left[\ln \left(1 + \frac{23.9 D P'}{\mu'} \sqrt{\frac{M'}{T'}} \right) \right] \quad (2)$$

where q = pressure x volumetric leakage rate, micron-liters/sec

D = capillary diameter, microns

P' = cabin pressure, psia

μ' = viscosity, poise

L = capillary length, cm

T' = temperature, °F

M' = molecular weight (average)

The most probable hole size is in the range of 1 to 10 microns (64).

The mass leakage of helium-oxygen mixtures is much less serious than once thought. There is actually little difference between the weight of proposed gas mixtures lost per day in the 5- to 7-psia range. For orifice flow, the leakage rate is nearly proportional to pressure. At pressures less than 7 psia, the same is true for capillary flow. As the pressure and molecular

weight increase, Equation (2) suggests that the leakage rate becomes proportional to the square of the pressure.

Table 11-9 compares the mass leak rate through capillaries of 3 microns in diameter for approximately similar mixtures and pressures calculated by the two independent groups using the different basic assumptions discussed previously. The leak rates appear quite insensitive to the different capillary lengths under study (1 and 6.3 mm). This remarkable agreement may have fortuitously arisen from the interaction between the slightly different pressures and compositions being studied and the differences in path length. In any case, these mass leak rates appear to be adequate for a first-order analysis of the weight tradeoffs of the different gas systems. The oxygen-neon mixtures appear to be slightly more favorable than the other mixtures for the 3-micron-diameter hole under consideration.

Table 11-9
Comparison of Mass Leakage Rates Assuming Capillary Flow
(After Roth⁽⁹⁰⁾)

Mass leak rate, lb/day, at pressures of—							Study
5 psia				7 psia			
100 percent O ₂	70 percent O ₂ 30 percent He	70 percent O ₂ 30 percent Ne	70 percent O ₂ 30 percent N ₂	50 percent O ₂ 50 percent He	50 percent O ₂ 50 percent Ne	50 percent O ₂ 50 percent N ₂	
1.0	0.811	0.702	0.988	1.13	0.810	1.70	Mason et al ⁽⁶⁴⁾ Boeing ⁽¹¹²⁾ Boeing ⁽¹¹²⁾ normalized to 5 psia O ₂ = 1 lb/day
1.05	.76	.....	1.05	1.08	.....	2.0
1.0	.72	.....	1.00	1.02	.....	1.90

Recent experimental studies on leakage generally confirm these theoretical predictions (12). The leakage ratio, by weight, of N₂ - O₂ to He - O₂ for total cabin pressures of 5, 7, and 10 psia were 1.23, 1.66, and 1.80 respectively. Data are available on total vehicular weight penalties dictated by these ratios for specific mission types (12, 90). Recent advances in sealing technology for spacecraft design have been reviewed (103). These principles should be brought to bear on the problem.

Leakage of space suits has been studied (55). For future EVA operations, leakage rates of less than 500 standard cc/min at 3.7 psia will be required. Not all prototype suits have been able to meet this requirement (55). Rx-2 and Rx-3 hard suits have attained a leakage of less than 25/cc/minute at 5 psia - 100% oxygen. It is reported that these leak rates do not appreciably increase with time, wear, and don-doff operations as in the case of contemporary soft suits (60).

Gas Storage Penalties

In calculation of weight penalties for life-support systems of cabins or PLSS backpacks, the interior gaseous environment must be considered (90).

The following data cover the weight and volume penalties to be assumed for the high-pressure gaseous and cryogenic storage of different atmospheric constituents. The storage of solid forms of oxygen such as superoxides, peroxides, chlorates and ozonides, as well as the electrolysis of water, were covered in Oxygen-CO₂-Energy, (No. 10). (See Table 10-33.) More data are available on solid oxygen storage (90).

It should be remembered that the tradeoffs for gas tankage or storage are often most sensitive to differences in spacecraft configuration and mission plan. This arises from the dependence of storage efficiency on the size and shape of the container, be it for gaseous or cryogenic systems. Only the basic factors covering most missions will be presented. Gas storage factor for PLSS back packs are covered in Reference (80).

High Pressure Gaseous Storage

The basic role of gaseous storage systems appears to be that of supplemental storage or storage for repressurization of the cabin when long-term storage prior to use makes it more efficient, especially in smaller cabin systems. The need for high delivery rate in repressurization also favors gaseous storage. A comparison with liquid systems under these conditions is presented subsequently.

The basic problem in this approach to gas storage is the minimization of container volume penalties by the use of elevated storage pressures without incurring excessive pressure shell weight. It can be shown that if the fluid stored acts like an ideal gas, the weight of container designed to hold a given charge is essentially independent of pressure while container volume is inversely proportional to pressure. Very-high-pressure storage appears to be the ideal goal. However, gas compressibility factors begin to limit the weight efficiency of storage. At pressures above several thousands of pounds per square inch, gases become less compressible. The decrease in compressibility is less serious for helium and neon than for oxygen and nitrogen (21).

Thus as pressure is increased, overall volume penalty passes through a minimum and actually increases because of overall shell-wall thickness. Pressure-level optimization studies for oxygen storage vessels indicate an optimum storage pressure of 7500 psia for equal pressure and volume criteria. (19, 52, 56). This psia was used in the Project Mercury system (73). Optimum storage vessels for pressure up to 9000 psia are currently under study by several companies (63). These vessels will be of greater value for helium and neon where compressibility factors play a lesser role.

If the rough sizing of a vehicle volume is available, the tradeoff between storage weight and volume can be made for any vehicle design. Data on this approach are available (19, 90). In all cases, the weight of tankage, W_T , and volume of tankage, V_T , may be given equal emphasis in minimizing the product ($W_T V_T$) or either of these factors may be over-emphasized, as in minimizing the products of

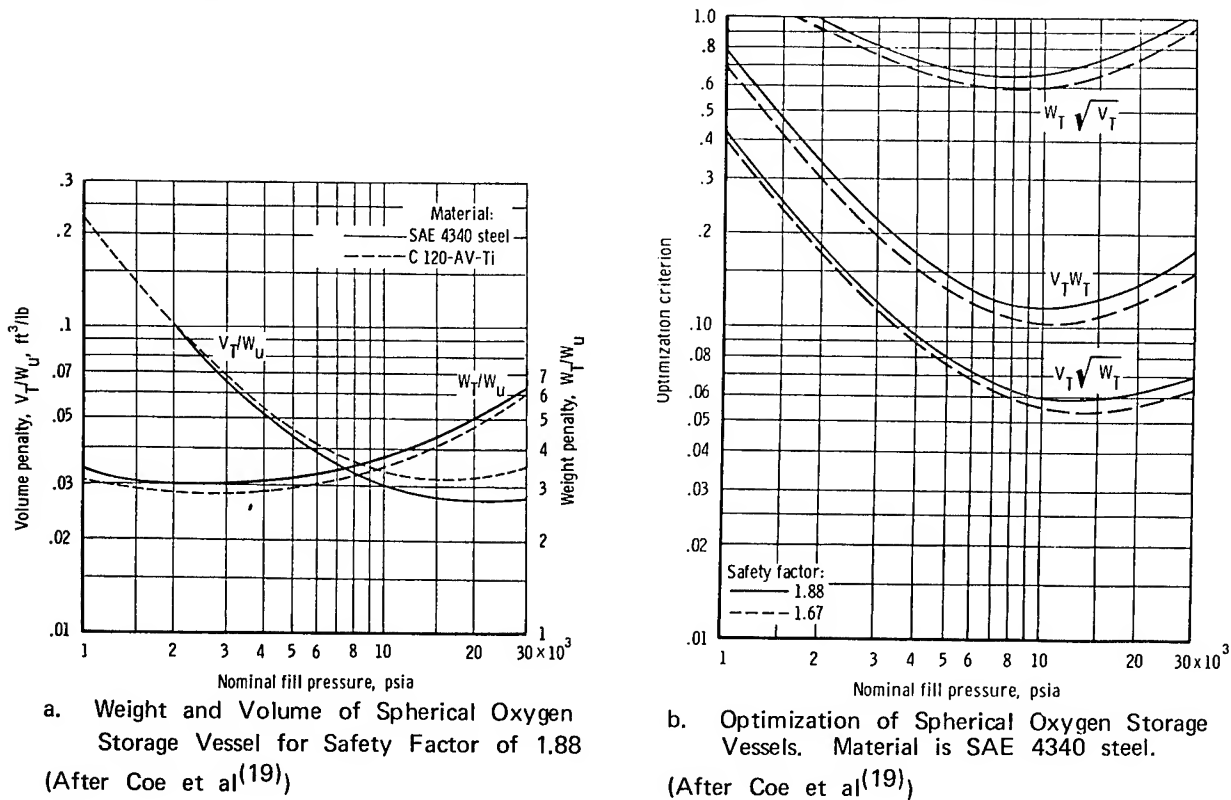
$$W_T \sqrt{V_T}, \text{ and } V_T \sqrt{W_T} \quad (3)$$

In all cases, it is assumed that the nominal fill temperature of the vessel is 530°R and maximum fluid use is 620°R. Storage-fluid end pressure is 30 psia. The gas compressibility factors for oxygen were computed from experimental pressure-volume-temperature data for nitrogen, assuming the law of corresponding states, the accuracy of the basic nitrogen data, and the close similarity of the two gases (19). Container structural analyses were given for simple geometries and were based upon the assumptions of true geometrical shape and of a low ratio of wall thickness to diameter. It is to be emphasized that more detailed analyses than those presented would be required to optimize structural design in a specific application. Particular attention would have to be given to vessel mounting requirements.

Figure 11-10a represents the variation with nominal charge pressure of the total weight and volume of spherical oxygen vessels for SAE 4340 steel

Figure 11-10

High Pressure Gaseous Storage of Oxygen - Weight and Volume Penalties



Parameter	Oxygen	Nitrogen
Optimum pressure, psia.....	10 500	9500
Weight penalty, W_T/W_U	3.46	3.66
Volume penalty, V_T/W_U , ft³/lb.....	0.0296	0.0446
Optimization criterion.....	0.1025	0.163

c. High Pressure Gas Storage Optimum Design

(After Rousseau et al⁽⁹¹⁾)

and titanium alloy C120 AV Ti. The fire safety of titanium pressure vessels for oxygen storage has been questioned, but will be included to show the weight savings (88). A fatigue failure criterion with a safety factor of 1.88 was used.

As discussed above, the weight and volume penalties show distinct minima. Minimum weight occurs at approximately 2500-psia charge pressure, indicating the deleterious effect of charge temperature tolerances on fluid load penalties at low charge pressures. Minimum vessel volume occurs at a charge pressure of approximately 20,000 psia for the steel vessels, showing the effects of increases in vessel wall thickness at higher charge pressures, as well as the increasing compressibility factor for the gas under these conditions. From other calculations, it appears that the pressures at which the weight and volume are minimum are apparently independent of the safety factor used in the design. However, the actual values of the weight and volume are directly related to the safety factor. Similar data for Inconel 718, stainless steel 301A (cryogenically stretched by Ardeforming), and Ti 6A 6V 2S may be found in Figure 7-15 of reference (3).

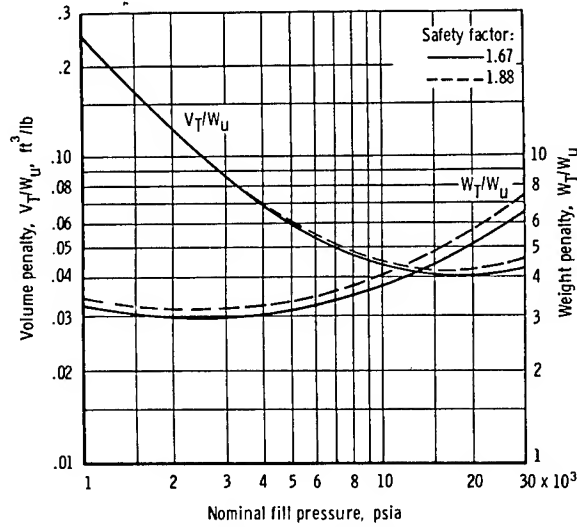
Total weights and volumes of spherical nitrogen storage vessels are shown in Figure 11-11a as functions of charge pressure level cases studied. Titanium was used as the vessel material for nitrogen. The results are generally similar to those obtained for oxygen, showing minima in vessel weight and volume in the pressure range studied. Similar data covering pressure up to 3500 psia for Inconel 718, stainless steel 301A (cryogenically stretched by Ardeforming) and Ti 6A 6V 2S may be found in Figure 7-15 of reference (3). Figure 11-11b shows the terms $W_T V_T$, $W_T \sqrt{V_T}$, and $V_T \sqrt{W_T}$ for spherical nitrogen vessels as functions of charge pressure level. Here the optimum charge pressure for minimum $W_T V_T$ is approximately 8000 psia in the case considered.

Table 11-10c summarizes the optimum values of weight and volume for oxygen and nitrogen vessels. It should be noted here that the weights plotted in Figures 11-10 and 11-11 do not include the weight of the lines, brackets, or valves; an allowance should be made for these accessories. The valve weight depends only on the number of vessels and on the number of valves installed on each vessel for redundancy and for installation requirements. Mounting bracket design depends primarily on the size of the vessel, on the number of vessels, and on the installation. These weights, in general, are small; an allowance for accessory weight should be made, however, in the total vessel weight.

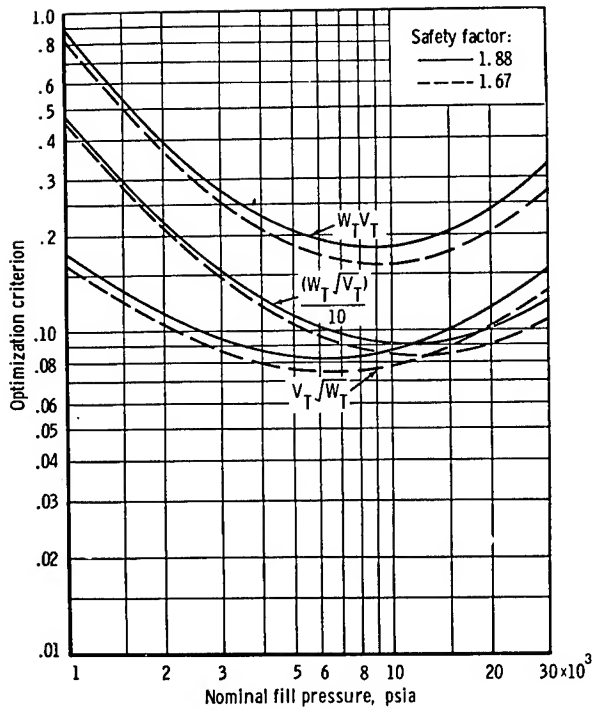
The weights and volumes of spherical helium vessels are shown in Figure 11-11c as functions of charge pressure level, using titanium as the pressure shell material. These data are limited to pressures below 6000 psia because of the lack of higher pressure-density data. The tendency of helium to diffuse through the metal may well limit the usefulness of higher pressures. Compressibility is not a factor with helium.

In the pressure range studied, the compressibility of neon appears to be the same as that of helium, both acting quite similar to an ideal gas (21). Since the density of helium at 0°C and 1 atm is 0.178 gm/l and that of neon

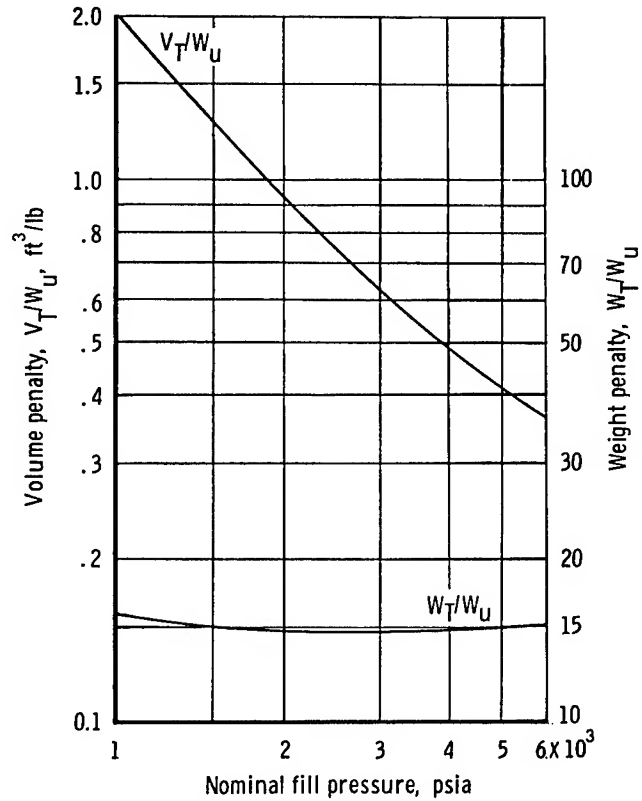
Figure 11-11
High Gaseous Storage of Nitrogen, Helium, and Neon
Weight and Volume Penalties
(After Coe et al⁽¹⁹⁾)



a. Weight and Volume of Spherical Nitrogen Storage Vessel (Material is Ti C-120 AV)



b. Optimization of Spherical Nitrogen Storage Vessels. (Material is Ti C-120 AV)



c. Weight and Volume of Spherical Helium Storage Vessels (See text for conversion to neon)

0.899 gm/l, the volume per pound of useful load should be reduced by a factor of about 5 and run parallel to the upper curve of Figure 11-11c. Similarly, the total vessel weights per pound of useful load should also be reduced by a factor of 5 and run parallel to the lower curve of Figure 11-11c. A less expensive mixture of 85 percent neon and 15 percent helium may be economically more feasible than pure gaseous neon.

The availability of mixed gas storage in one container for repressurization purposes appears to be a great advantage of high pressure gaseous systems. This system is indeed attractive only for this purpose since the requirement for stable use of both constituents precludes its maintenance use in cabins where unavoidable erratic leaks occur. Even in the event of constant-leak systems, the mixed gas form alone is not suitable for cabins where crew occupancy or workload can vary from time to time and no parallel control of leak rate is feasible.

Cryogenic Storage

The cryogenic storage of fluids offers several distinct advantages over high-pressure storage of the low boiling-point fluids such as oxygen and nitrogen. These advantages are a higher fluid storage density at low to moderate pressure, reduced container weight per unit of stored mass, provision of potential refrigeration or cooling sources as heat sinks (170 Btu/lb for liquid oxygen or nitrogen when heated to room temperature).

The major defects are the sensitivity to unexpected heat leaks and the complexity of delivery in zero gravity. These defects require special attention to insulation needs, single-phase fluid expulsion, phase separation for venting, and quantity measurement. Cost, development time, servicing equipment, standby penalties, and limited expulsion capability are other disadvantages.

Two major classes of cryogenic liquid storage systems are used. They specify either mode of storage or method of pressurization. The fluid may be stored as a single phase of fluid or as a two-phase mixture of fluid and vapor requiring special separation techniques. The pressurization may, in turn, be accomplished by use of externally supplied gas or by thermal energy added by means of electric power or a heat exchanger in the storage space.

The following three types of systems appear to be most commonly suggested for zero-gravity space cabin use:

- 1) Supercritical, single-phase, thermal pressurization
- 2) Subcritical, single-phase, helium bladder expulsion
- 3) Low-pressure, two-phase, vapor or liquid delivery

Because weight tradeoffs are quite sensitive to the specific form of cryogenic storage involved, detailed knowledge of the different systems is necessary. Summaries of the different systems (19, 90) and more detailed discussions are available (17, 105).

Some of the major internal and environmental factors determining the design weight of the hardware are: (90)

- 1) Inner shell:
 - (a) Internal fluid pressures of up to 3000 psia
 - (b) Launch and reentry loads
- 2) Outer shell:
 - (a) Compression load from buckling pressure of atmosphere
 - (b) Effect of insulation and vacuum beneath it
 - (c) Dynamic loads
- 3) Insulation:
 - (a) Evacuation required to improve insulation and prevent liquefaction of atmospheric components within the space, with subsequent deterioration of performance
 - (b) Temperature and pressure variation inside the craft
 - (c) Compressive loads passing from outer to inner shell
 - (d) Allowable heat-leak contribution from lines and support members
 - (e) Ideal operational thermal requirements: no loss standby for a given holdup with pressure buildup from fill pressure to maximum pressure; constant pressure operation at minimum delivery rate with no venting in thermally pressurized tanks; and no external heat input other than vessel heat leak

It is quite apparent that all of the above factors must be considered in detail before a gas-specific cryogenic weight tradeoff can be made. Minor variation in assumptions about any of these factors can alter the cryogenic storage penalty in any specific mission.

In presenting typical cryogenic-system storage weights, the following assumptions are made:

- 1) Vessels are spherical.
- 2) Control and accessory weights are ignored; this is an important point.
- 3) Room temperature properties of materials are used to give weights which could be lowered if this factor becomes critical in a design tradeoff.
- 4) Vessel pressurization is achieved by means of electrical heaters, heat exchangers, or simply by heat leakage from the outer shell, resulting in a uniform temperature throughout the mass of the fluid stored. In practice, this condition may not be realized unless suitable means are provided for mixing the fluid inside the container, especially in a zero-gravity environment, where there are no natural convection currents. In a general analysis of the type presented here, temperature uniformity must be assumed, although in practice, a computer program can be used to cover the effects of non-uniformity of temperature (112).

- 5) In general, the line and support heat leaks are assumed to constitute a fixed proportion of the insulation heat leaks. This assumption greatly simplifies the calculations, since these heat leaks depend on the geometry of the lines and supports of a particular vessel and can only be calculated exactly when the detailed design of the vessel is performed. Based on previous analysis of lines and supports, it appears that the value of the ratio of line and support heat leaks selected for the numerical examples (0.20 insulation heat leaks) is conservative for large vessels, and can be achieved for small vessels by careful design of the lines and support members.
- 6) Heat exchangers, instrumentation, and control valves were not considered in the analysis. They are closely related to mission requirements and are therefore treated as separate components; as such, these items, together with the storage vessel itself, form a subsystem. An analysis of these subsystems has been presented elsewhere in a comparison of the total gas-system weight penalties (90). The subsystem weight should be relatively constant for different gases stored. It should be remembered, however, that for small vessels up to 10 inches in diameter, the weight of such items may in certain applications be an important part of the subsystem weight.

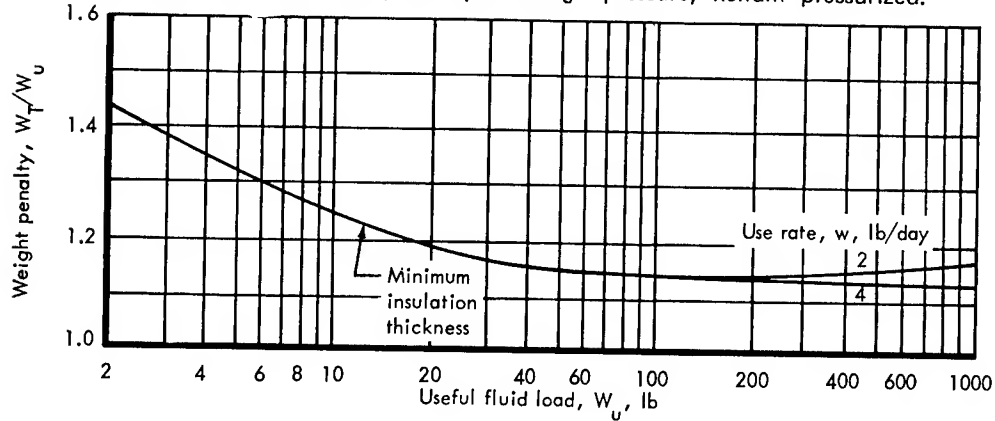
Other assumptions used in the numerical examples, such as constant ambient temperature, constant pressure operation, constant rate of flow, etc., are clearly stated wherever used. Details regarding the specific structure of the cryogenic systems shown in figures are available (3, 19, 90, 91). Advances in the design of new multilayered cryogenic insulation (97) may reduce these tankage penalties which should be considered to lie on the conservative side.

Figure 11-12 presents conservative weight and volume penalties for cryogenic oxygen storage and Figure 11-13 gives comparable data for cryogenic nitrogen systems.

For missions of long duration, the obligatory heating of cryogenic fluid may influence tradeoff studies (3, 90). Subcritical storage initially offers weight advantages over its supercritical counterpart; however, this advantage diminishes in cases of long standby of several hundred hours and small useful fluid payloads. This is due to the fact that the quantity of heat required to pressurize the fluid from 1 atmosphere to an operating pressure of about 100 psia is only about 30 percent of that required for supercritical storage at about 900 psia. This effect is especially noticeable at small payloads where insulation presents a larger part of the total weight of the system. For long systems having long standby times, venting can be used in both supercritical and subcritical systems. In such cases, a tradeoff between vent fluid and insulation must be made. It should be stated that anticipation of such long standby times for oxygen systems is probably unrealistic, but may be realistic for inert gas systems needed to replace leakage gas in mixed gas systems.

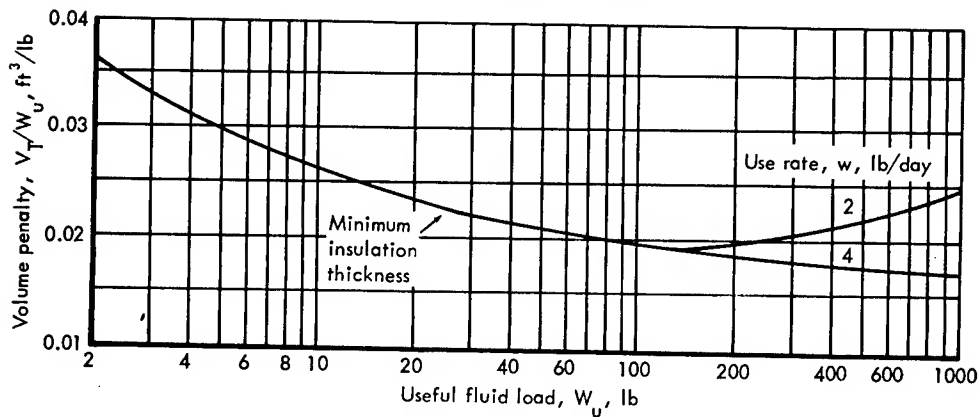
Figure 11-12
Cryogenic Storage of Oxygen - Weight and Volume Penalties
(After Rousseau et al⁽⁹¹⁾)

Supercritical Storage-Spherical, Rene 41 inner shell, Al 6061-T6, outer shell, 800 psia design pressure; Subcritical Storage-Spherical, Al inner shell, Al 6061-T6, outer shell, 100 psia design pressure, helium pressurized.



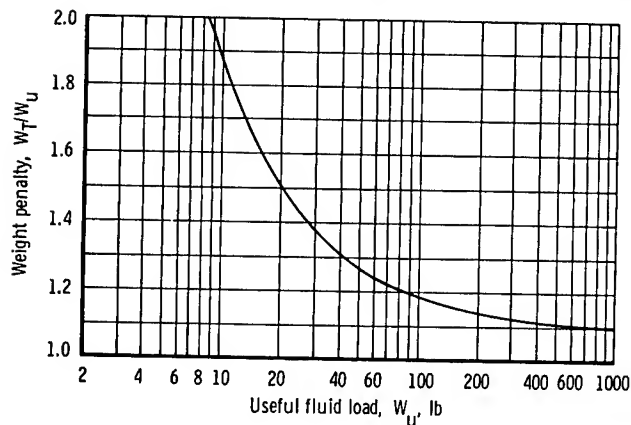
a. Tankage Weight Penalty, Supercritical Storage

Note that for flow rate higher than 4 lb/day, the vessel weight penalty is determined by the minimum insulation thickness.



b. Tankage Volume Penalty, Supercritical Storage

Note that for flow rate higher than 4 lb/day, the vessel volume penalty is determined by the minimum insulation thickness.

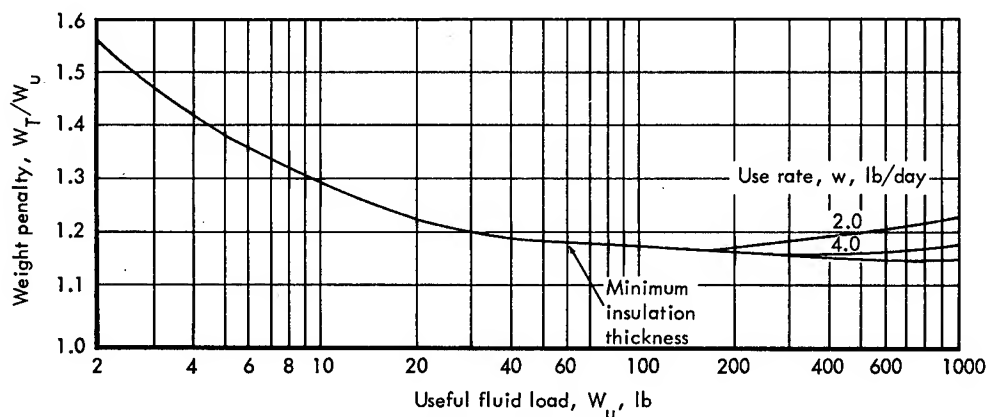


c. Tankage Weight Penalty, Subcritical Oxygen Storage

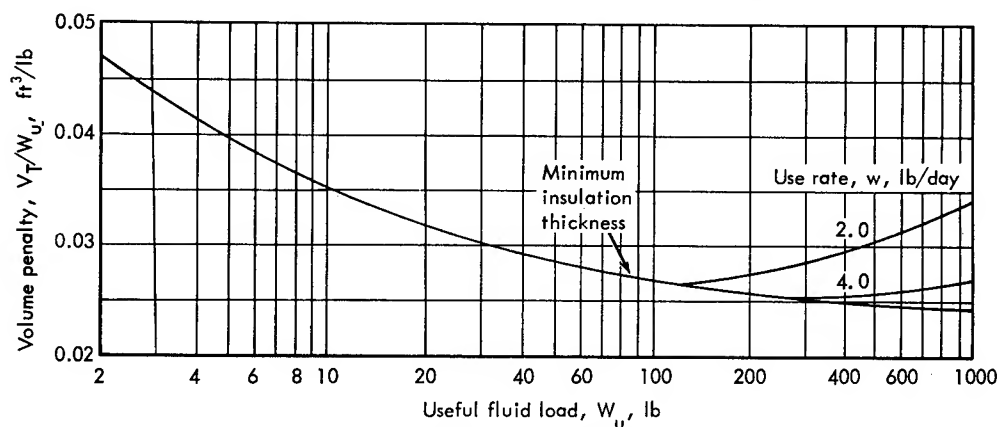
Figure 11-13

Cryogenic Storage of Nitrogen - Weight and Volume Penalties
(After Rousseau (91))

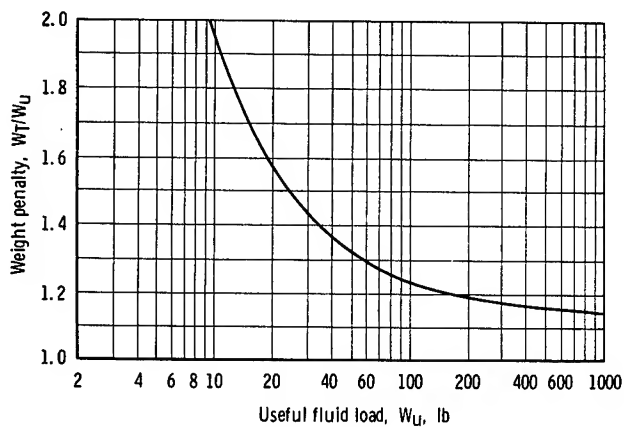
(See Figure 11-12 for design specifications of the supercritical and subcritical systems; supercritical nitrogen design pressure is 725 psia)



a. Tankage Weight Penalty for Supercritical Nitrogen Storage



b. Tankage Volume Penalty for Supercritical Nitrogen Storage



c. Tankage Weight Penalty for Subcritical Nitrogen Storage

Experience with small, flight-rated, cryogenic helium systems is limited. Because the rate of use of helium will usually be low, the heat-leak factor becomes great in determination of weight tradeoffs for helium systems (90). For example, in a 2-man 30-day mission, an error of only 1 Btu/hr in heat-leak calculation of the design can increase the total system weight by 50 pounds or nearly 50 percent (52). If the vehicle has a hydrogen tank for a fuel-cell reactant supply or for a propulsion engine, consideration should be given to mounting the helium tank within the hydrogen tank. This method results in low-temperature gaseous storage of helium with a fluid storage density comparable to that of liquid helium. The advantage is that the helium tank does not require insulation and therefore the tank design is simply a high-pressure gaseous storage vessel. A thermodynamic analysis must be made for each mission to establish the minimum expulsion rate, final density, and optimum storage pressure.

The storage of helium is particularly sensitive to use rate. Because of obligatory venting, pressure-variant methods proposed for shorter missions cannot be used in longer missions (63). In operation of the pressure-variant mode, the tank pressure is allowed to increase slowly during the mission. A portion of the energy transferred into the liquid is used to expel the demand and thereby to reduce the insulation requirement. For 30-, 60-, and 90-day missions with 2 or 3 men, the pressure-variant tanks with a maximum pressure of between 850 and 1000 psia have the same weight penalty as isobaric tanks. At first glance it would appear that tanks for the longer mission would be larger and would entail a greater weight penalty because of the same demand flow to cover a constant leak rate. However, the greater quantity of fluid stored in the longer mission allows a greater amount of energy to be absorbed by the stored cryogenic fluid per unit increase in pressure. This counteracts the other factors mentioned above. It should be pointed out that utilization of the pressure-variant mode may not be acceptable if helium is to be capable of supplying the high flow rate for compartment repressurization in the launch or orbit-stabilization phases of a space mission. At high use rates, the weight penalties will decrease. To indicate the change in penalty involved, for a 30-day 2-man mission with isobaric tank, data for helium weight penalties are plotted against use rate in Figure 11-14. The

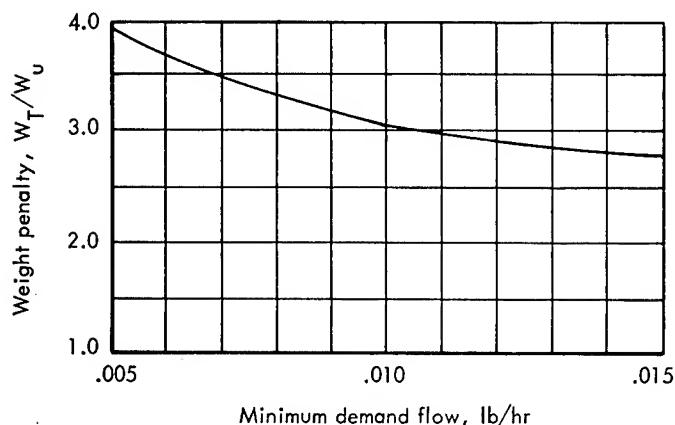


Figure 11-14

Weight Penalty Change for Cryogenic Helium Storage Due to Minimum Demand Flow

Data covers a 30-day mission, 1000 psia isobaric operation.

(After Mason and Potter⁽⁶³⁾)

W_T/W_U decreases from 3.8 to 2.75 as demand flow increases from 0.005 to 0.15 lb/hr. These rates are probably conservative figures. Work in progress on the ground-support helium tank for the Apollo lunar excursion module and on small cryogenic vessels may give a more definitive answer to weight penalties (9). Because of the lack of operational experience with small cryogenic helium systems in spacecraft and the indicated sensitivity of the system to small design errors, it would be wise to approach helium tradeoffs with great caution.

Unfortunately, little work has been done on flyable neon cryogenic systems. Small cryogenic neon units have been made for laboratory use, but no published data are available (63, 65). Neon appears to be a much more favorable liquid for cryogenic storage than is helium. Because of the high heat of vaporization and liquid density, much less boiloff of neon occurs (65). In commercial containers of 25-liter size (8 to 12 lb of liquid), the normal evaporation rate of nitrogen is 1.9, neon is 6.3, and helium is 18.1 ft³ (STP) per day. The percentage of boiloff per day is 0.33 percent for liquid nitrogen, 0.54 percent for liquid neon, and 3.0 percent for liquid helium. The gross weights for 1000 ft³ (STP) of gas are 92 pounds for nitrogen, 63 pounds for neon, and 31 pounds for helium. On a volume basis, neon also offers 3.5 times more refrigeration than does liquid hydrogen and 40 times more than liquid helium. Preliminary studies indicate that a subcritical system designed for 30 days of minimum leakage at 0.012 lb/hr with an initial charge of 20 pounds and a pressure-variant operating mode from 450 psia to 1500 psia will have a dry weight of only about 17 pounds (63). Therefore, $W_T/W_U = 37/20 = 1.85$ for neon compared with an optimized 3.8 for helium and about 1.2 for nitrogen.

Since the boiling point of liquid neon is above that of liquid hydrogen, gaseous storage in a liquid hydrogen tank is impossible. Because of the favorable aspects of neon from a physiological point of view, more work on the cryogenic storage of this gas appears appropriate. The problem of storage of the technical grades of neon contaminated with 15 percent helium also requires further study.

Solid lithium azide has been used as a source for generation of nitrogen gas (19). Weight penalties of W/W_{N_2} of about 1.14 on the basis of chemical material balance alone (no storage penalties for the azide or lithium oxide product) approach cryogenic storage penalties of nitrogen (Figure 11-13). In addition, the reaction is difficult to control and presents a safety problem.

Criteria for Selection of Space Cabin Atmospheres

Selection of space cabin atmosphere must be analyzed from both a physiological and an engineering point of view (87, 90). The most significant interface is the thermal. Biothermal considerations in the design of space cabins have been covered on pages 6-18 to 6-43 of the Thermal Environment, (No. 6). Some of the engineering implications are noted here.

The problem of thermal comfort in spacecraft cabins appears to be generally solved. Selection of ideal cabin air and wall temperature for any given gaseous mixture is very sensitive to the exercise rate and clothing

insulation values assumed. Selection of the ideal diluent from the point of view of thermal comfort is entirely an engineering decision based on minimum weight and power. Some of the basic principles at question can be outlined. Table 6-14 presents a comparison of the thermodynamic and aerodynamic properties of the several candidate atmospheres. It can be shown that for a constant volumetric flow such as is required for removal of water vapor or trace contaminants, the blower power is approximately proportional to the density of the gas mixture ($\sim \rho$). For constant heat transfer capacity, the fan power is inversely proportional to the square of the density and to the cube of the heat capacity ($\sim 1/\rho^2 C_p^3$) (90).

From the thermal conductivity and densities of the different gas mixtures one can calculate the relative velocities required to attain the same heat transfer coefficient (h_c) and the relative power required to attain these velocities. Table 11-15 represents this comparison normalized to 7 psia 50% O₂ - 50% N₂ as equal 1. The density and thermal conductivity factors definitely favor helium-oxygen mixtures in this regard.

Table 11-15
Power Penalties for Space Cabin Ventilation and Dehumidification
as Related to Atmospheric Gases
(After Boeing⁽¹¹⁾)

a. Velocities for $h_{c1} = h_{c2}$ and Fan Power for Different Gas Mixtures

	O ₂ - N ₂		O ₂ - He		O ₂
	7.0 psia	5.0 psia	7.0 psia	5.0 psia	5.0 psia
$k \sim \text{Btu/hr-ft-}^\circ\text{f}$	0.0153	0.0153	0.0386	0.0286	0.0155
$\rho \sim \text{lbs/ft}^3$	0.0365	0.0268	0.022	0.0206	0.0279
$V \sim \text{ft/min.}$	47.	64.	12.5	25.	60.
Power $\sim \text{watts}$	63.	62.	10.	19.	61.
Relative power	1.	.86	.16	.30	.97

b. Power Required to Remove Water from a Gas Stream
Relative to 7 Psia O₂ - N₂

	O ₂ - N ₂		O ₂ - He		O ₂
	7.0 psia	5.0 psia	7.0 psia	5.0 psia	5.0 psia
Power/Watts	1.00	0.72	0.60	0.53	0.72

The removal of water is a thermodynamic process which constitutes a large percentage of the thermodynamic load on the atmospheric control system (90). The amount of water vapor added by the occupants can be measured by the so-called latent heat load whereby each pound of water evaporated into the air is represented by about 1050 Btu. Latent personal heat loads of from 70 Btu/hr (resting) to about 1000 Btu/hr (severe exercise) can be expected as extreme ranges, with an average of 150 to 200 Btu/hr over a 24 hour period for each person in a multi-manned crew. The power penalties for water removal in a space cabin appear to be the major factor in determining the mass flow of the atmosphere purification system (90). The pressure drop in the system

plays a major role in the gas-dependent tradeoffs. The mass flow of gas (\dot{W}_g) required to remove water from any atmosphere is inversely related to the specific humidity of the atmosphere (ϕ)

Therefore, comparing any 2 gas mixtures,

$$\dot{W}_{g2} \sim \dot{W}_{g1} \left(\frac{\phi_1}{\phi_2} \right) \quad (4)$$

The relative pressure drop (ΔP) for a gas flow system is related to the \dot{W}_g and density (ρ) as follows:

$$\Delta P \sim \frac{\dot{W}_g^2}{\left(\frac{\rho}{\rho_{\text{Standard}}} \right)} \quad (5)$$

Since relative power for any gas may be determined by the relationship, power $\sim \dot{W}_g \Delta P / \rho$, (11)

$$\text{Power}_2 = \text{Power}_1 \left(\frac{\dot{W}_{g2}}{\dot{W}_{g1}} \right) \left(\frac{\rho_1}{\rho_2} \right) \frac{\Delta P_2}{\Delta P_1} = \left(\frac{\phi_1}{\phi_2} \right) \left(\frac{\rho_1}{\rho_2} \right) \left(\frac{\Delta P_2}{\Delta P_1} \right) \quad (6)$$

Since it can be shown that: (90)

$$\frac{\dot{W}_{g2}}{\dot{W}_{g1}} = \frac{\phi_1}{\phi_2} = \frac{m_2}{m_1} \quad (7)$$

and

$$\frac{\rho_2}{\rho_1} = \frac{m_2}{m_1} \quad (8)$$

and

$$\frac{\Delta P_2}{\Delta P_1} = \frac{\dot{W}_{g2}}{\dot{W}_{g1}} \times \frac{\rho_1}{\rho_2} \quad (9)$$

therefore,

$$\frac{\text{Power}_2}{\text{Power}_1} = \frac{m_2}{m_1} \quad (10)$$

Since the power required to remove a given mass of water from a gas mixture is simply proportional to the molecular weight, the relative power requirements for the different gas mixtures under consideration can be determined as shown in Table 11-15b, where the values are normalized to 7psia O₂ - N₂ as = 1.

The engineering considerations in the selection of space-cabin atmospheres appear to be dominant. A comparison of the weight, power, complexity, and cost penalties for the several atmospheres of Table 11-15 have been made (90). Weight factors include such items as: structure of cabin wall; atmospheric leakage; tankage penalties for cryogenic and superoxide storage of gas; weight and power-weight penalties for ventilation fan, atmospheric processing fan, and equipment cooling fans of the air conditioning system; and weight-dependent reliability factors. Such transient dynamic phenomena as decompression time after puncture and physiologic or equipment overloads resulting from failure of the environmental control system must also be included. A key factor in an engineering evaluation is the relative weights and complexities of such power sources as fuel cells, solar cells and nuclear systems. The economic factors in choice of atmosphere are development time, maintenance, convertibility, crew acceptance, and cost.

Unfortunately, the nature of the specific mission in question plays an overwhelming role in coloring the engineering factors. One atmosphere cannot be selected as ideal for all missions. The weight penalties are especially sensitive to the mission factor. For a 2-man orbiting laboratory of 30 days duration, up to 200 lbs. of weight may be saved by selection of the ideal atmosphere. In the example just chosen, 5 psia 30% helium - 70% oxygen gave the minimum penalty and 7 psia 50% nitrogen - 50% oxygen gave the maximum penalty (90). The penalty for neon-oxygen was almost exactly the same as that for the ideal helium-oxygen. What is gained in the more efficient cryogenic storage of neon is lost in the less efficient power utilization in the air condition system. What is quantitatively true for this case may not be true for other mission types though there would be a general trend in the above direction.

Tables 11-16a, b, and c summarize the factors which must be considered in selection of space cabin atmospheres.

Atmosphere Control

Presence of an inert gas in a space cabin mixture complicates the control of space cabin atmospheres. A cabin with 5 psia oxygen can have a control system based on a simple sensor for total cabin pressure. As oxygen is consumed and carbon dioxide is absorbed, the cabin pressure drops and more oxygen is allowed to enter the cabin to offset this pressure drop. Mixed-gas cabins require partial-pressure sensors for one of the two gases in order to maintain a constant percentage of both gases in the face of simultaneous oxygen consumption by the crew and variable, mixed-gas leakage from the cabin.

Many different P_{O_2} sensors are available, but no device with ruggedness and long-term reliability of the simple anaeroid sensor of the 5 psia oxygen system has been developed (79). A flyable, ultraviolet-absorption P_{O_2} meter is currently under development for the NASA (77). There are still some unresolved problems in the area of the interference by water vapor and carbon dioxide in the ultraviolet band being sampled. Polarographic sensors all appear to have a limited duration of performance without adjustments or

Table 11-16

Criteria for Selection of Space-Cabin Atmospheres
(After Roth(90))

a. Physiological Factors

FACTOR ^a	MIXED 7 PSIA			MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION ORDER ^b
	1) 3.5 PSIA O ₂ 3.5 PSIA N ₂	2) 3.5 PSIA O ₂ 3.5 PSIA H ₂	3) 3.5 PSIA O ₂ 1.5 PSIA N ₂	4) 3.5 PSIA O ₂ 1.5 PSIA H ₂	5) 5 PSIA O ₂		
1. Aural atelectasis 10, 11	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5	
2. Pulmonary atelectasis 10, 11	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5	
3. Vital Capacity reduction 10	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5	
4. Hemolytic anemia 10, 11	No Problem	No Problem	No Problem	No Problem	Has occurred in lab; ? significance	(1 2 3 4) 5	
5. Urinary abnormalities 10, 11	No Problem	No Problem	No Problem	No Problem	Has occurred in lab ? significance	(1 2 3 4) 5	
6. Radiation Sensitivity 3	No Change	No Change	No Change	No Change	No change at this pressure	(1 2 3 4) 5	
7. Voice Pitch Change 11	Insignificant	Minimal	Insignificant	Minimal	Insignificant	1 (3 5) (4 2)	
8. Decompression time prior to symptoms of hypoxia 12	Longest available	Intermediate	Next to shortest	Shortest available	Intermediate	1 (5 2) 3 4	
9. Alteration of trace contaminant effects 13	None expected	None expected	None expected	None expected	Has occurred in lab	1 2 3 4 5	
10. Abdominal gaseous distress 11	Least, same as 2	Least, same as 1	Most, same as 4 and 5	Most, same as 3 and 5	Most, same as 3 and 4	(1 2) (3 4 5)	
11. Decompression Sickness a) Bends 12	Rare but most susceptible	Same as 1	Very rare intermediate susceptibility	Same as 3	Probably will not occur when fully denitrogenated	5 (4 3) (1 2)	
b) Neurocirculatory collapse 12	Extremely rare; most susceptible	Extremely rare; intermediate susceptibility	Very extremely rare	Insignificantly low possibility	Probably will not occur when fully denitrogenated	5 4 3 2 1	
c) Ebullism survival time 12	Least time	Intermediate time	Intermediate time	More time	Most time	5 4 (2 3) 1	
12. Explosive Decompression 12	Extremely rare; most susceptible	Extremely rare; low susceptibility	Extremely rare; intermediate susceptibility	Extremely rare; lowest susceptibility	Extremely rare; intermediate susceptibility	4 2 (3 5) 1	

Continued on next page

Table 11-16 (continued)

a. Physiological Factors (continued)

FACTOR ^a	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION ORDER ^b
	1) 3.5 PSIA O ₂ 3.5 PSIA N ₂	2) 3.5 PSIA O ₂ 3.5 PSIA H ₂	3) 3.5 PSIA O ₂ 1.5 PSIA N ₂	4) 3.5 PSIA O ₂ 1.5 PSIA H ₂	5) 5 PSIA O ₂	
13. Blast overpressure 7, 12	Intermediate lung damage; worst gas emboli	More favorable than 1	More lung damage; less dangerous emboli than 1 Intermediate	More lung damage; less dangerous emboli than 2 Intermediate	Same lung damage; less dangerous emboli than 3. Most dangerous	(2 4) 5 3 1
14. Flash blindness from meteoroid penetra- tion. 2	Least dangerous	Same as 1	Intermediate	Intermediate	Most dangerous	(1 2) (3 4) 5
15. Possible metabolic side effects 11	Least	Slightly more than 4	Slightly greater than 1	Slightly less than 2	Most likely	1 3 4 2 5
16. Tolerance of high air temperature 6, 11	Least	Most	Slightly more than 1	Next to 2	Same as 3	2 4 (3 5) 1
17. Changes in bacterial flora of skin and mouth 11, 13	Least	Same as 1	Much less expected than in 5	Much less expected than in 5	Does occur in lab	(1 2) (3 4) 5

a. Bold faced numbers refer to sections of the compendium where the problem is covered.
b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

Table 11-16 (continued)

b. Fire and Blast Hazards

FACTOR ^a	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION ORDER ^b
	1) 3.5 PSIA O ₂ 3.5 PSIA N ₂	2) 3.5 PSIA O ₂ 3.5 PSIA H ₂	3) 3.5 PSIA O ₂ 1.5 PSIA N ₂	4) 3.5 PSIA O ₂ 1.5 PSIA H ₂	5) 5 PSIA O ₂	
1. Burning rate of fabrics and plastics	Slowest rate	Greater than 1 but hardest to ignite by contact with hot solid Probably same as 1	Slightly greater rate than 2	Greater than 3 but harder to ignite by contact with hot solid Probably same as 3	Fastest burning rate	(2 1) (4 3) 5
2. Flame temperature of burning hydrocarbon vapor.	Lowest		Slightly higher than 1		Highest	(2 1) (4 3) 5
3. Decompression time to extinguish flame.	Longest	Intermediate	Next to shortest	Shortest	Intermediate	4 3 (2 5) 1
4. Selectivity of cabin materials	Least restrictive	Same as 1	Intermediate	Same as 3	Most restrictive	(2 1) (4 3) 5
5. Flash oxidation from meteorite penetration	Least dangerous	Slightly more dangerous than 1	Slightly more dangerous than 1	Slightly more dangerous than 3	Most dangerous	1 2 3 4 5
6. Reduction of fire hazard by zero-gravity	Slightly more reduced than 3	Probably most reduced; most diffusible inertant at flame front.	Slightly less than 4	Slightly less than 2	Markedly reduced but least susceptible to zero-gravity effects	2 4 1 3 5
7. Toxicity of oxidation products of atmosphere.	Most toxic; oxides of nitrogen	Least toxic	Slightly less than 4	Least toxic	Same as 4	(2 4 5) (3 1)
8. See # 13 in Table c	----	----	----	----	----	----
9. Overall fire hazard	Least severe	Same as 1	Intermediate	Intermediate	Most severe	(1 2) (3 4) 5

a. Source - Reference 11-91.

b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

Table 11-16 (continued)

c. Engineering Factors for 30-Day, 2-Man Mission - Other Missions May Have Other Factors

FACTOR ^a	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3. 5 PSIA O ₂ 3. 5 PSIA N ₂	2) 3. 5 PSIA O ₂ 3. 5 PSIA He	3) 3. 5 PSIA O ₂ 1. 5 PSIA N ₂	4) 3. 5 PSIA O ₂ 1. 5 PSIA He		
1. <u>Gas Storage</u> Overall tankage weight penalty	Less than 2)	Greatest	More than 5)	Less than 1)	Least	5 3 4 1 2
Weight of diluent gas used	Most	Slightly more than 4)	Slightly less than 1	Least used	None	5 4 2 3 1
Total gas storage weight.	Most	Intermediate	Intermediate	Least	Slightly more than 4)	4 5 (2 3) 1
2. <u>Fan Power Weight</u> Atmosphere control	Most	Slightly more than 4	Intermediate	Least	Intermediate	4 2 (3 5) 1
Ventilation and heat transfer	Most (same as 3 and 5)	Least	Most (same as 1 and 5)	More than 2	Most (same as 1 and 3)	2 3 (5 4 1)
3. Controls, weight and complication	More complicated than 5	Same as 1	Same as 1	Same as 1	Least weight and complication	5 (1 2 3 4)
4. Total ECS weight penalty	Most	Intermediate	Intermediate	Least	Intermediate	4 5 (2 3) 1
5. Development time and cost	Intermediate	High	Intermediate	Slightly more than 2 (if small diluent tankage)	Least	5 (1 3) (2 4)
6. Reliability of hardware	Less than 5	Less than 1	Same as 1	Less than 3	Most	5 (1 3) (2 4)
7. Computability with current re-entry modules	Least	Same as 1	Intermediate	Intermediate	Most	5 (3 4) (1 2)
8. Sensitivity to extension of active missions to 90 days	Little	Some increase in storage efficiency less than 4	Little	Value does gain slightly because of increased storage efficiency.	Little	4 2 (1 3 5)
9. Sensitivity to stand-by operations	Gaseous storage insensitive, cryogenic is same as 3 and 5	Sensitive due to greater heat sink of cryogenic helium; gaseous may leak at high pressure.	Same as 1	Slightly greater than 2 due to greater heat leak; gaseous may leak at high pressure.	Same as 1	(1 3 5) 2 4

a. Factors are discussed in sections 6 and 11 of this compendium and in References 11-12 and 11-90.

b. Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

replacement of the sensor elements (54). Chromatographic techniques are available but these are costly in terms of weight and are not as reliable as might be desired in flight equipment. A flyable chromatograph is under development (114, 115). Time-of-flight mass spectrometers also have the same problems of reliability and flight worthiness (8). Mass-spectrometers suitable for flight operations are also under development, but no reliability data are available as yet (63, 76).

Fuel-cell sensors have been developed which may operate as part of the hydrogen-oxygen fuel cell of the main power supply or be self-contained instruments. Again, no reliability data are available. Flyable hardware is now under development (109).

Two new approaches to flyable oxygen-sensing devices appear encouraging. A zirconium-oxide, solid-electrolyte cell with high temperature operation is under development (99) as are thin-film gold and zinc oxide processes (15 116). No reliability data are as yet available.

Sensing inert gas components is another approach to the problem. Helium, by virtue of its unusual physical properties, presents the greatest opportunity for flyable instrumentation. Such physical approaches as thermal conductivity, sound resonance, mass and coincidence spectrometry, and others, offer good potential, but no flight hardware has been developed. An ionization gage has been developed for analysis of helium-oxygen mixtures in gas dynamics laboratories (66). In spite of the complexity of the circuitry, the modification of such a device for spacecraft use may be a fruitful approach.

A thermal conductivity meter has been used in physiological experiments to separate helium from other respiratory gases and contaminants (67). An acoustic gas analyzer has also been used in respiratory physiology (34).

The weight penalty and reliability factors associated with the additional controls as well as the sensors in mixed gas systems must also be accounted for. Several control instruments for mixed-gas control are available (14, 69). It has been estimated that additional weight for a mixed-gas control above that for 5 psia oxygen will range from 12 to 15 pounds (53). It has also been estimated that for the Apollo spacecraft, substitution of a 7 psia oxygen-nitrogen system for the present 5 psia system would increase the total gas systems weight penalty, including sensors, controls, and tankage, by only 52 pounds or about 10 percent (63).

Studies are underway to establish analytic techniques for control of atmospheres and other components of integrated life-support systems (100).

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12. PRESSURE

Prepared by

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This section covers static pressure, slow and rapid (explosive) decompression, and blast overpressure. The partial pressure environment is covered in Oxygen-CO₂-Energy, (No. 10) and Inert Gas (No. 11).

Static Pressure

The lower limits of static pressure are determined primarily by the availability of an adequate P_{O_2} in the lungs for unimpaired performance (Figure 12-1) and decompression sickness (see below).

The physiological relations between the percentage of oxygen in the atmosphere of an aerospace vehicle and the total pressure of that atmosphere shown in Figure 12-1 are based on continuous exposure for one week or more.

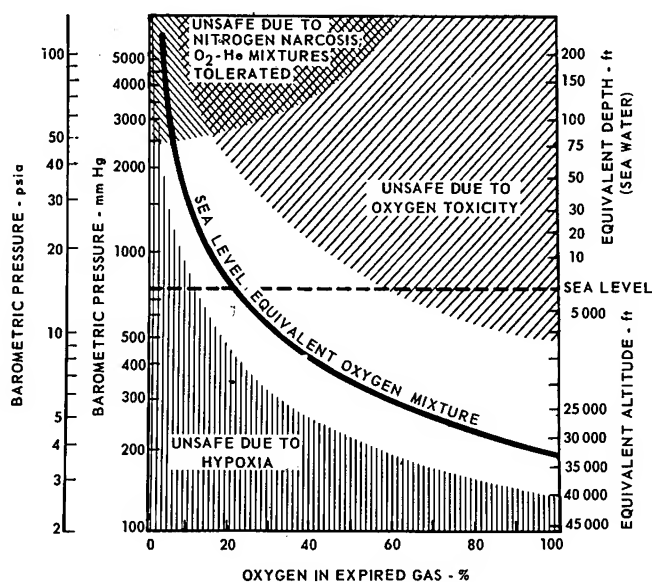


Figure 12-1

The Effect of Barometric Pressure and Altitude on Oxygen Required for Normal Functions

(Adapted from the Space Handbook (115))

Atmospheric air contains 21% oxygen by volume. At sea level, this leads to a blood saturation of 95%. To maintain the same degree of oxygen in the blood at lower pressure, the percentage of oxygen in the atmosphere must increase as shown by the "sea level equivalent" curve. The clear unimpaired performance zone, bounded by the hatched lines, indicates the range of variation that can be tolerated without performance decrement (see Oxygen-CO₂-Energy (No. 10)).

Prolonged exposure to low oxygen levels lying to the left of the clear unimpaired performance zone requires acclimatization. Acclimatization is accomplished by continuous exposure to successively lower pressures with

no intermediate return to higher pressures. Acclimatization to 25,000 feet requires 4-6 weeks and performance is still impaired.

The upper limits of pressure are determined by nitrogen narcosis and oxygen toxicity as indicated by the hatched lines in Figure 12-1. The maximum oxygen tolerance (definite pathology) for long periods is currently under investigation. The role of nitrogen and trace contaminants on the symptoms and signs of oxygen toxicity in the 90-100% oxygen range is still open to question, as shown in the hatched area extending into the zone of unimpaired performance (100). (See Inert Gas, No. 11). A P_{O_2} of 258 mm Hg (5 psia-100% oxygen) has been tolerated in operational space cabins for up to 14 days without performance decrement, though abnormal hematological findings were present which may have been related to the elevated partial pressure of oxygen (92, 100). Table 11-8 covers ground-based experiments in atmospheres of different pressures and compositions.

Charts and nomograms are available relating different total pressures and partial pressures of oxygen and inert constituents to the equivalent alveolar oxygen (89).

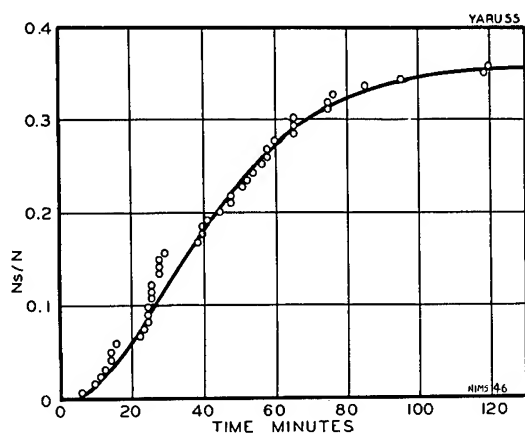
Slow Decompression and Decompression Sickness

During prolonged exposure to atmospheres that contain physiologically inert gases (nitrogen, hydrogen, helium, argon, xenon, and krypton), the body fluids (water and fat) contain amounts of these gases in solution proportional to the partial pressure of the gas in inspired air and to the solubility of the gas in water and fat at body temperature. If the body is subsequently exposed to a much lower barometric pressure, inert gases tend to come out of solution (the phenomenon of effervescence). Oxygen, carbon dioxide, and water vapor also diffuse rapidly into evolved bubbles of gas. Such bubbles, if they form in tissues, may produce pain, especially around the joints. Bubbles within fat cells may cause rupture of the cell walls, allowing fat to enter the circulation. If bubbles form within blood vessels, they are carried to the small terminal vessels of the lungs or the brain where they lodge, cutting off the blood supply of the tissues behind them.

The symptoms caused by evolved gas are known collectively as decompression sickness. This disorder may be mild or it may cause incapacitation. For any one individual, it is unpredictable in its onset and course, though symptoms are rarely seen during the first few minutes of exposure to low barometric pressure. Many factors, among them temperature, muscular work, age, body build, etc., influence susceptibility to decompression sickness and the time course of symptoms (94, 105). A general time course of symptoms experienced in decompression from sea-level air to altitude is shown in Figure 12-2. The fraction of a group having symptoms in a given time interval, is usually at a maximum between twenty and sixty minutes. After two to three hours exposure, very few subjects get new symptoms. The integral of the time curve, a plot of the cumulative fraction of those who have developed any self-judged degree of symptomatology against the time, is an ogive curve having a point of inflection within the same twenty to sixty-minute interval. The ogive curve of Figure 12-2a represents, in most direct

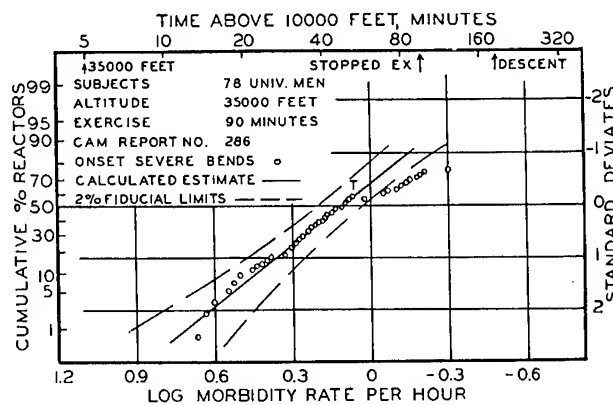
Figure 12-2

Time Course of Symptoms in Decompression Sickness Upon Exposure to Altitude from Prior Equilibration to Air at Sea Level



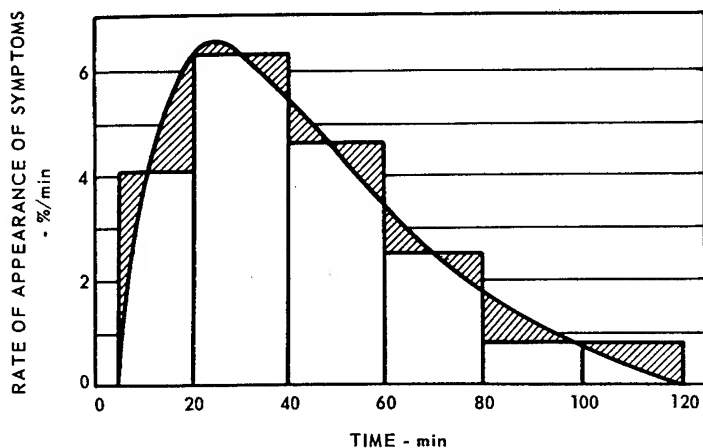
a. The Cumulative Fraction of Group Developing Severe Symptoms of Decompression Sickness as a Function of Duration of Exposure

(After Nims (94))



b. Statistical Treatment of Relationship Between Duration of Exposure and Symptoms of Decompression Sickness

(After Nims (94))



c. Rate of Appearance of New Symptoms

(After Nims (94) from the data of Anthony (2))

and simple way, the quantitative information that can be gained about the group in their reaction to low pressure. The specific shape of the ogive is a function of the final pressure and the secondary factors mentioned above.

Figure 12-2b indicates that if the logarithm of the time of onset of severe bends after exposure to 35,000 ft with exercise is plotted against the cumulative percent reactors expressed in terms of standard deviates, a nearly linear relationship is obtained.

Figure 12-2c shows the percent of exposed subjects per minute experiencing new symptoms (bends of grade 2 or > and chokes) at given times after exposure to 38,000 ft at rest from previous sea level conditions. The curve is thought to reflect the size history of a typical gas bubble in the sensitive tissue (94).

The varied symptoms and pathological physiology of decompression sickness have been reviewed in great detail (1, 44, 102). One can summarize the pathological physiology of the symptom complexes by dividing them into several categories: bends, chokes, skin manifestations, circulatory collapse, and neurological disorders. The relative incidence of the different symptoms varies with the type and partial pressure of the gas of previous equilibration, the level of exercise, and final altitude (102). Relative incidence from work in altitude chambers are available (13, 14).

Bends, the most common symptom, is manifested by pain in the locomotor system. This pain usually begins in the tissue around joints and extends distally along the bone shaft. Pain tends to occur in joints that are being flexed. It is deep and poorly localized with periods of waxing and waning. Relief is obtained by relaxation of the part or application of external pressure to the overlying tissues. Symptoms may spontaneously disappear.

The next most common symptom complex is chokes. Chokes refer to a syndrome of chest pain, cough, and respiratory distress. It usually requires longer altitude exposure than that required for bends. It commences with a burning pain under the breast bone during deep inspiration which is relieved by shallow breathing and gradually becomes more severe and constant. Paroxysms of coughing become more frequent and are followed by cyanosis, anxiety, syncope, and shock.

Skin lesions, causing itching and a red blotchy rash, usually occur only after prolonged altitude exposure and are associated with or presage more serious manifestations of decompression sickness. About 10% of those cases going on to neurocirculatory collapse present previous skin changes. It appears that passage of emboli to the skin is the most probable mechanism.

Neurocirculatory manifestations are the most serious. Cardiovascular symptoms are varied: fainting, low blood pressure, coronary occlusions, heart arrhythmias, and shock have all been seen. Rarely, severe and progressive peripheral vascular collapse develops one to five hours post-exposure to altitude. This reaction may or may not have been preceded by fainting. Signs and symptoms of shock with or without neurological findings are seen. Delirium and coma are more common when neurological findings are present. All fatalities following altitude exposure are preceded by this picture of delayed shock. It usually develops in subjects who have experienced severe decompression sickness, especially severe chokes, but may be preceded by few or no symptoms. The types of neurologic symptoms run the gamut of almost every acute neurologic disorder. Convulsions, partial retinal blindness and headaches are the most common.

Several semi-empirical equations have been proposed for rough, first-order, prediction of bends frequency after decompression from atmospheres containing a P_{N_2} other than that of air at sea level (8, 9, 10, 37, 102). These have few other empirical data in their support (10, 34, 37, 55, 68). Unfortunately, decompression from a space cabin involves such conditions. One can assume that a space-cabin atmosphere containing inert diluent should have about 3.5 psia (180 mmHg) of oxygen and a total pressure of 5 to 7 psia for minimum weight penalty (103). This would allow for 1.5 to 3.5 psia of inert

gas. From the point of view of decompression, the lower the equilibrium pressure level of inert gas, the lower the bends hazard upon subsequent decompression to a lower pressure. This would make the cabin with 7 psia 50% inert gas - 50% oxygen more hazardous than one with 5 psia - 70% inert gas - 30% diluent. Prediction of the incidence of bends after decompression from the more hazardous of the mixtures to a space suit pressure of 3.5 psia has been attempted (102). Inadequacy of the empirical data precludes a very precise prediction. The semi-empirical equation of Bateman (8, 9), suggests that after total equilibration to the 7 psia 50% nitrogen - 50% oxygen environment, a well-conditioned astronaut when decompressed to 3.5 psia (35,000 ft) at rest will have less than a 1% chance of experiencing mild, grade I-II bends. If moderate exercise is imposed, the incidence could rise to about 7%. For the general population with only average cardiovascular status and conditioning through exercise, the bends incidence in exercise conditions may be 10-15%. If the space suit pressure could be raised to 5 psia without compromising the mission, the bends incidence should drop by about a factor of 3. Complete equilibration with a 5 psia - 30% nitrogen - 70% oxygen environment and subsequent decompression to 3.5 psia would probably result in no symptoms even with heavy exercise.

In comparison, Figure 12-5 suggests that direct decompression from air at sea level to 3.5 psia presents a more serious hazard. At rest, about 25% of the astronauts would probably experience the bends. Depending on the degree of exercise, from 50 to 100% of the individuals exposed could experience moderate to severe bends. Many would experience chokes and neurocirculatory collapse. Pre-flight or in-flight denitrogenation is certainly an operational requirement in such circumstances.

The decompression hazard prior to the time period of complete equilibration with the space-cabin atmosphere (about 8 to 12 hours) is more difficult to predict. The amount of prior denitrogenation by preoxygenation techniques is a critical factor. Data are available for specific profiles (10, 34, 37). Theoretically, five hours of preoxygenation should reduce the symptom rate to that of the equilibrium condition noted for 7 psia 50% oxygen - 50% nitrogen (see below). Shorter periods of denitrogenation possibly dictated by operational restrictions will increase the decompression hazard above this level during the early phases of flight (102).

Presence of inert gases other than nitrogen further complicates predictions of bends, chokes, or neurocirculatory collapse hazards in space cabins. Several theoretical studies of the problem have been made. Both the formation of stable gas micronuclei (10, 37) and rate of bubble growth (102) have been considered as limiting factors in the incidence of symptoms. Both approaches suggest that neon-oxygen mixtures should be safer than helium-oxygen or nitrogen-oxygen as far as bends are concerned. Both indicate that there should be little difference between oxygen-helium and oxygen-nitrogen of the same composition. The few empirical data to the point suggest the helium-oxygen produces slightly more frequent symptoms than oxygen-nitrogen and the symptoms are more difficult to resolve by recompression (10, 34). It should be kept in mind that these experiments were performed under specific M. O. L. profiles in which the body was not

fully denitrogenated and gases were in the unsteady state. Results may well be different for conditions of complete saturation.

It is important that predictions specify whether or not the partial pressure of gas assumed prior to decompression represents equilibrium or non-equilibrium conditions. Age and physical conditioning are also major factors determining incidence. Figure 12-3 represents age dependence of symptoms with no special selection for physical conditioning. Body fat: lean weight ratios are also important (87).

The amount of physical exertion is also important. The effect of exercise rate on incidence of bends after sea-level equilibration in air is seen in Figure 12-4. There is a steady increase in incidence from rest to about 10 deep knee bends every 15 minutes. Incidence varies significantly with the type of exercise.

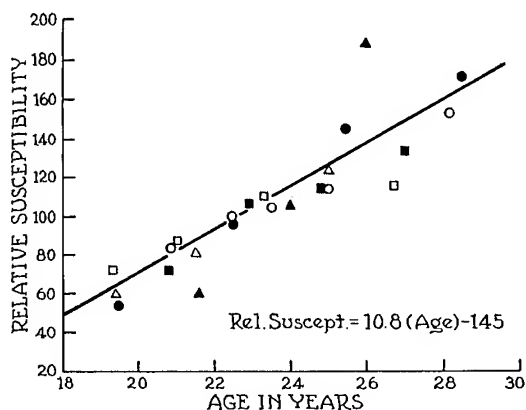


Figure 12-3

Relationship Between Age and Relative Susceptibility to Bends Upon Exposure from Sea Level to Altitude

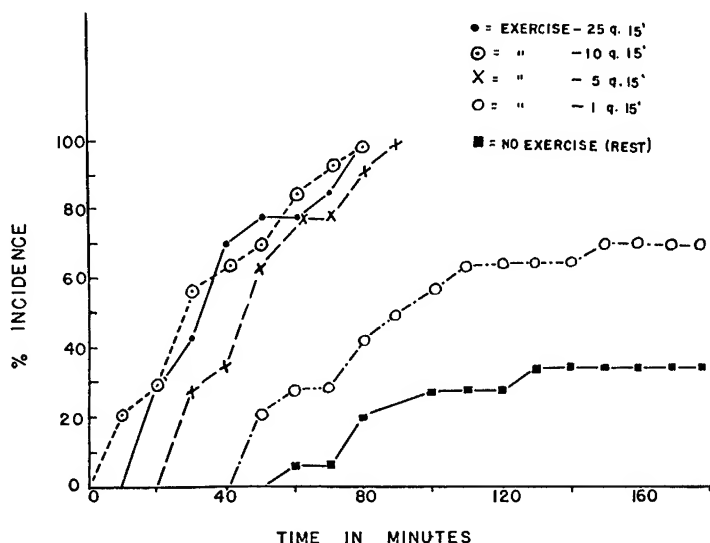
(After Gray (50))

Figure 12-4

Effect of Exercise on Incidence of Bends

Comparison of cumulative incidence of decompression sickness in a group of 14 subjects exposed from sea level equilibration in random fashion to variable degrees of exercise during simulated flights at 35,000 feet (179 mm Hg or 3.5 psia). Exercise was deep knee bends.

(After Ferris and Engle (44))



Protection is afforded by denitrogenation. Total denitrogenation by exposure to 100% oxygen atmospheres for periods of 16 hours or more can be expected to reduce the incidence of bends to zero. Shorter time periods of denitrogenation result in progressively greater incidence of bends. The percent symptoms retained tend to be equal to the percent of residual body nitrogen after previous equilibration with air at sea level. The half time of the second tissue compartment for nitrogen (68-73 minutes) seems to correlate best with the half time of symptom reduction by preoxygenation upon exposure with exercise to 35,000 feet (179 mm Hg or 3.5 psia) (65). For young subjects in good physical condition the half time of nitrogen depletion and incidence of symptoms can be as low as 20 minutes. The dependence of the denitrogenation rates and retained symptoms on age and physical condition in several studies are seen in Figure 12-5. The broken lines represent loss of protection produced by one hour of air breathing after the denitrogenation. Various preoxygenation schedules have been tested in simulation of decompression from space cabins (10, 34, 37, 55, 68).

Denitrogenation schedules for protection against bends caused by exposure to space suit pressures in early phases of flight can be made from Table 12-6 which represents conservative protection factors taken from Figure 12-5. The table is designed to cover groups which eliminate nitrogen slowly. It applies to a suit pressurized at 35,000 feet (179 mm Hg or 3.5 psia) with moderate exercise at altitude. The average nitrogen elimination curves of groups greater than 24 years of age are used in the tables for the category "probable protection." Curve #10 of Figure 12-5 appears in the table as the

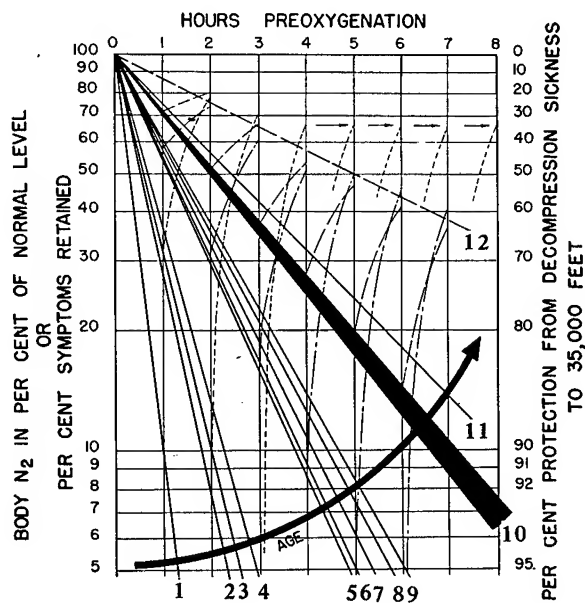


Figure 12-5

Compilation of All Data Bearing on Rate of Protection by Preoxygenation and Rate of Nitrogen Loss from Critical Tissues

Curves 6, 7, and 9 represent data of three different investigators on same age group.

Legend

1. 18 yr old group (fastest curve) - 35,000 ft.
2. 18 yr old group (average curve) - 35,000 ft.
3. <24 yr old group (fastest curve) - 35,000 ft.
4. 17 yr old group (average curve) - 38,000 ft.
5. 27 yr old group (average curve) - 38,000 ft.
6. <24 yr old group (average curve) - 35,000 ft.
7. <24 yr old group (average curve) - 35,000 ft.
8. Mixed group average protection rate - 35,000 ft.
9. <24 yr old group (average curve) - 35,000 ft.
10. <24 yr old group (slowest curve) - 35,000 ft.
11. 35 yr old group (average curve) - 38,000 ft.
12. Single subject (slowest curve) - 35,000 ft.

(After Jones (65))

Table 12-6
Protection^a of Groups^b Compared to Ascent Without Preoxygenation
(After Jones⁽⁶⁵⁾)

Preoxygenation, hr	Minimum protection, percent	Probable protection, percent
0.5.....	16	26
1.0.....	29	45
1.5.....	41	59
2.0.....	50	70
2.5.....	58	77
3.0.....	61	83
3.5.....	70	87
4.0.....	75	91
4.5.....	79	
5.0.....	82	
5.5.....	85	
6.0.....	86	
6.5.....	89	
7.0.....	91	

^a Zero protection equals incidence of decompression sickness of group without preflight oxygen when ascending to altitude at 4000 feet per minute.

^b For group prediction and not for individual prediction.

"minimum protection" category. Unless age or nitrogen elimination characteristics of a group are known, prediction should be made with "minimum protection" category. "Protection" is given in percent improvement over the expected condition of preflight oxygenation for that group and ascent to altitude no faster than 4,000 ft/min. For example, if at 35,000 feet a group experiences 70% symptoms, and 50% forced descents with no preoxygenation, after one hour of preoxygenation one would expect from Table 12-6, a "minimal protection" group of:

$$\begin{aligned} 70 \times 0.29 &= 20.3\%; \quad 70 - 20.3 = 49.7\% \text{ symptoms} \\ 50 \times 0.29 &= 14.5\%; \quad 50 - 14.5 = 35.5\% \text{ descents.} \end{aligned}$$

Preflight contingencies requiring return to air breathing entail a loss of protection. Table 12-7 represents the protection retained after breathing oxygen for periods of 1 to 7 hours followed by air exposures of 1/2 to 1 hour.

The rate of depletion of inert gas stores in the body after breathing 100% oxygen have been determined for nitrogen and helium. The rate of inert gas elimination follows the exponential equation:

$$dQ_g/dt = k_1 A_1 e^{-k_1 t} = k_2 A_2 e^{-k_2 t} + \dots + k_n A_n e^{-k_n t} \quad (1)$$

Table 12-7
Protection^a Retained When Preoxygenation is Interrupted with Air Breathing
(After Jones⁽⁶⁵⁾)

	O ₂			Air			O ₂			Air			O ₂			Air			O ₂			Air			O ₂			Air		
Time, hr.....	1	1/2	1	2	1/2	1	3	1/2	1	4	1/2	1	5	1/2	1	6	1/2	1	7	1/2	1									
Minimum protection, percent.....	29	26	20	50	40	33	64	54	46	75	62	53	82	68	60	86	74	62	91	74	62									
Probable protection, percent.....	45	33	25	70	52	39	83	62	46	91	67	50	95	70	52	97	72	54	97	73	54									

^a Zero protection equals incidence of decompression sickness of group without preflight oxygen when ascending to an altitude of 35 000 feet at 4000 feet per minute.

where: Q_g = the amount of gas lost (cc)
 t = time (minutes)
 k = exponential time constant of each storage compartment
 A = original volume of gas in each exponential storage compartment (cc).

The exponential equation for nitrogen elimination is (65):

$$\frac{dQ_{N_2}}{dt} = 51.2e^{-.462t} + 16.8e^{-.087t} + 10.3e^{-.025t} + 3.3e^{-.0047t} \quad (2)$$

This is plotted as Figure 12-8a.

The rate of helium elimination is much less certain. Three independent studies have given 3 different equations (11, 42, 66). Uncertainty regarding the early period of elimination is a major cause of difficulty. A desaturation equation defining the fractional rate of helium elimination after a 12 hour saturation period is (42):

$$R_t = 0.25e^{-0.5t} + 0.045e^{-0.135t} + 0.0022e^{-0.025t} + 0.0006e^{-0.0073t} \quad (3)$$

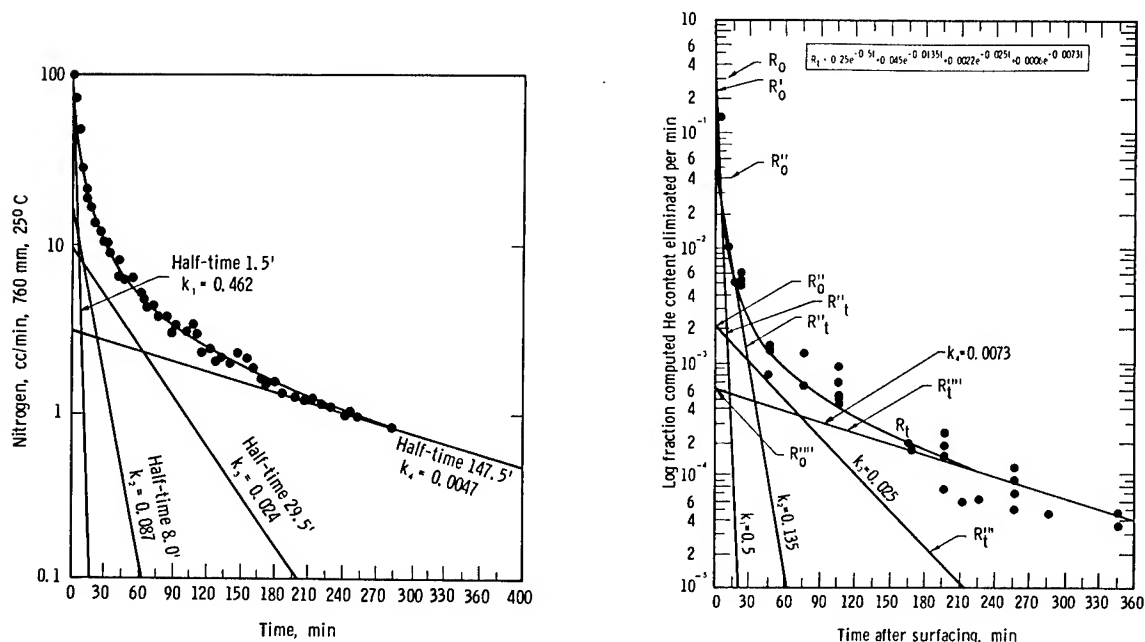
where: R_t is the fraction remaining at any time, t .

Figure 12-8b is the graphic representation of this equation with constants indicated for each exponential.

Further development of recent attempts at theoretical analysis of gas kinetics in diving may allow more definitive predictions of inert gas hazards in the space operations (67, 72, 102, 108, 112). These electrical and pneumatic computer techniques appear particularly promising. Another potential tool in substantiating any theoretical analysis is the ultrasound

Figure 12-8

Rate of Inert Gas Elimination from Body



a. Rate of Nitrogen Elimination After Switching from a Respiratory Mixture of Air at Sea Level to 100% O₂

(After Jones (65))

b. Rate of Helium Elimination Following 12-Hour Exposure to 1.72 or 2.05 Atmospheres (absolute) Helium In Oxygen

(After Duffner and Snider (42))

technique for bubble detection (53, 88). If the technique can be refined and calibrated it could possibly be used to determine in a more quantitative way the relationship between body movement, tissue supersaturation, the generation of bubbles, and symptoms (102).

A review of the treatment of decompression emergencies in space operations is now available (26). Recompression to the maximum allowable pressure of suit and cabin in 100% oxygen would probably offer the best immediate solution (86). In space chambers the standard U.S. Air Force approach is recommended (87). Supportive treatment of severe emergencies has been reviewed (26).

Protection of astronauts in space by elastic fabric or foam sponge suits is currently under study (54, 96A, 119). This approach may counter the bends problems, and, at the same time, reduce the inconvenience and reduction of mobility presented by current pressure suits.

Several equations have been proposed for rough, first-order, prediction of bends frequency after decompression from atmospheres containing a P_{N_2} other than that of air at sea level (10, 102). These have little empirical data in their support. Unfortunately the physical condition of the subjects and the equilibrium conditions of inert gas saturation have varied in different studies

(9, 10, 34, 102). The data of Tables 11-2 and 11-3 and Figure 11-4 of Inert Gas (No. 11) may be used in the calculation of these equations.

The slow leakage of gas from space cabins is covered in Inert Gas (No. 11).

Rapid (Explosive) Decompression

Rapid decompression of spacecraft or suits can result from accidental trauma or meteorite penetration. Post-meteoritic disruption of space cabin walls and accompanying fire and blast hazards has been reviewed (101). Decompression of space suits by meteorites is a constant hazard during EVA operations (101). Damage to the body by low-velocity impacts is covered under Impact in Acceleration (No. 7). Little is known of hypervelocity impact effects in humans or animals (101). Protection against meteoroid penetration of space suits is accomplished by a combined thermal and anti-meteoroid coverall (85).

Antimeteoroid Coveralls

In the Gemini G4C extravehicular space suit, the extravehicular coverlayer consisted of an outer protective layer of high-temperature-resistant (HT-1) nylon, a layer of nylon felt for micrometeoroid protection, seven layers of aluminized Mylar and unwoven Dacron superinsulation, and two additional layers of high-temperature nylon for micrometeoroid shock absorption. The meteoroid protective coverlayer design used on the Gemini IV mission was proof tested with simulated meteoroids. The Gemini G4C suit configuration was qualified to provide a 0.999 probability of no penetration, P_0 , of the bladder. In a system pressurized to 3.7 psig, samples of 4 by 4" swatches of the meteoroid coverlayer on the bladder were impacted with simulated meteoroids of cork and epoxy, glass and porosilicate in the 5 to 27 km/sec range. Since these projectiles approximate the meteoroidal energy that is absorbed by the coverlayer, a corresponding P_0 for a 10-minute exposure was determined. The exposure was for a near-Earth orbit and 25 ft² of surface area on the space suit. A pyrex glass sphere 274 microns in diameter at a velocity of 6 km/sec approximates the energy necessary to obtain a P_0 of 0.999 for a 10-minute exposure

Samples of lexan and merlon polycarbonate visor material were pressurized to 3.7 psig and impacted with glass spheres accelerated to hypervelocity with the AVCO RAD light gas gun. The projectile impact energy was progressively increased, until the sample was perforated or a leak occurred. An examination of the targets revealed that the 0.098-inch-thick merlon and lexan withstood the impact of a 0.0156-inch glass sphere at a velocity of 6 km/sec without spall or leakage. This projectile energy, when extrapolated to meteoroidal velocity and density, corresponded to a P_0 of 0.99993 for 135-minute exposure. The need for reduced coverlayer bulk to improve unpressurized suit mobility and pilot comfort was noted.

The G4C space suit assembly used in the Gemini VIII mission was similar to the one used in the Gemini IV mission. However, the configuration of the micrometeoroid protective layers of the extravehicular coverlayer was modified to utilize two layers of neoprene-coated nylon in lieu of the nylon felt and 6-ounce, HT-1 nylon, micrometeoroid layers. Also, the extravehicular pilot used integrated pressure thermal gloves in lieu of the pressure gloves and overgloves used for Gemini IV. The gloves were designed to protect the hands from micrometeoroids and to prevent conductive heat transfer through the glove palms caused from touching surfaces with temperatures ranging from 250° to -150° F. Structurally and functionally, the gloves were similar to the standard intravehicular pressure gloves with a pressure bladder, a restraint layer, and a wrist connector. A 1/8-inch-thick, flexible, insulating, silastic material was provided on the palm side of the glove for conduction insulation. Micrometeoroid protection was through additional layers of fabric used in the layup of the glove. The micrometeoroid testing of the new coverlayer material demonstrated a P_0 of 0.999 for worst-case conditions. The extravehicular space suit components were not used for EVA because of early termination of the mission. However, the reduced coverlayer bulk resulting from the change in micrometeoroid protective materials improved the unpressurized suit mobility for the intravehicular operations.

The addition of the Astronaut Maneuvering Unit (AMU) to the flight plan for Gemini IX-A required extensive modifications to the coverlayer of the G4C space suit. The lower forward-firing and downward-firing AMU thrusters impinged upon the legs of the suit. Temperatures as high as 1300° F were possible at the AMU thruster impingement areas on the suit surface. Since the HT-1 high-temperature nylon, which is normally used for the coverlayer, is not recommended for continuous use at temperatures above 500°F, new suit materials were required. A stainless steel fabric was incorporated into the legs of the suit coverlayer to protect it from the heat generated by AMU thruster impingement. Analysis and testing also indicated that the temperatures inside the thermal insulation layers of the coverlayer would exceed the melting temperature of the aluminized Mylar. Aluminized H-film was developed and found to be adequate for the temperatures expected and, when separated by layers of fiberglass cloth, worked well as a high-temperature thermal insulation. Eleven layers each of aluminized H-film and fiberglass cloth were incorporated into the legs to provide thermal protection during AMU operations. A standard extravehicular coverlayer layup was utilized for the upper torso and the steel outer cover with aluminized H-film and fiberglass cloth was used as thermal insulation for the legs. No meteoroid penetrations of this system were recorded.

The coverall of Gemini X and XI suits were similar to the Gemini VIII. The Gemini XII space suit used by the pilot was a slightly modified version of the one used for the Gemini IX-A mission. The stainless steel fabric on the legs was replaced with high-temperature nylon, and four layers of the aluminized H-film and fiberglass cloth superinsulation were deleted from the suit legs. The coverlayer thermal layup was quilted to the first layer of micrometeoroid protective material. A rectangular pattern was quilted over the torso area, which strengthened the thermal layer and reduced the possibility of tears or rips in the aluminized H-film and aluminized Mylar layers. The suit operated well; no meteoroid punctures were recorded.

The physiological response to rapid decompression must be considered from several points of view: The time of useful consciousness, damage to the lungs by explosive decompression, and the ebullism syndrome.

Time of Useful Consciousness After Rapid Decompression

The time of decompression (τ), after puncture or disruption of a cabin wall needed to attain a given ratio of final to initial pressure (P_f/P_i), is a function of the orifice coefficient (C_d) and the ratio of orifice area (A) to cabin volume (V) (17, 103). Figures 12-9a and b represent this relationship for several different gas mixtures suitable as space cabin atmospheres (102, 103). The equation assumes sonic orifice flow for isothermal and isentropic decompression. A sample calculation for isothermal flow using Figure 12-9a: For a hole 1/2 inch in diameter, an orifice coefficient (C_d) of 1, and a psia oxygen can be determined from Figure 12-9a by using the ratio 3.5 to 5.0 or 0.7 to give:

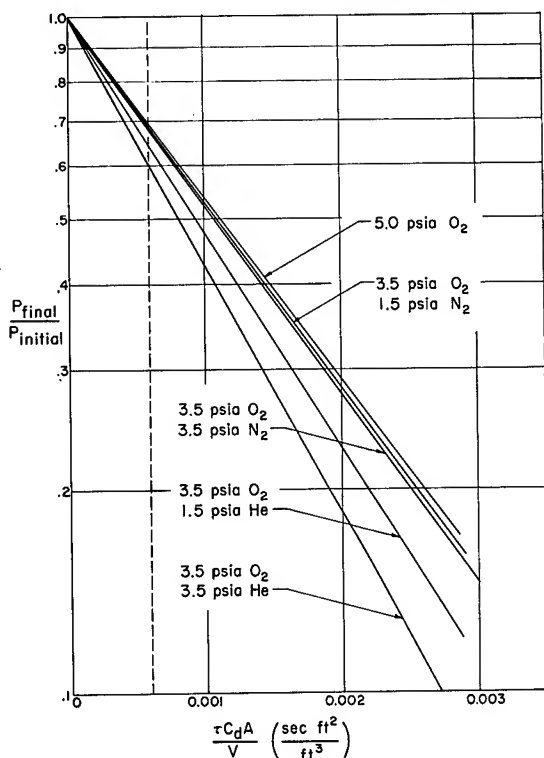
$$\frac{\tau C_d A}{V} = 0.000575 \left(\frac{\text{sec ft}^2}{\text{ft}^3} \right)$$

and

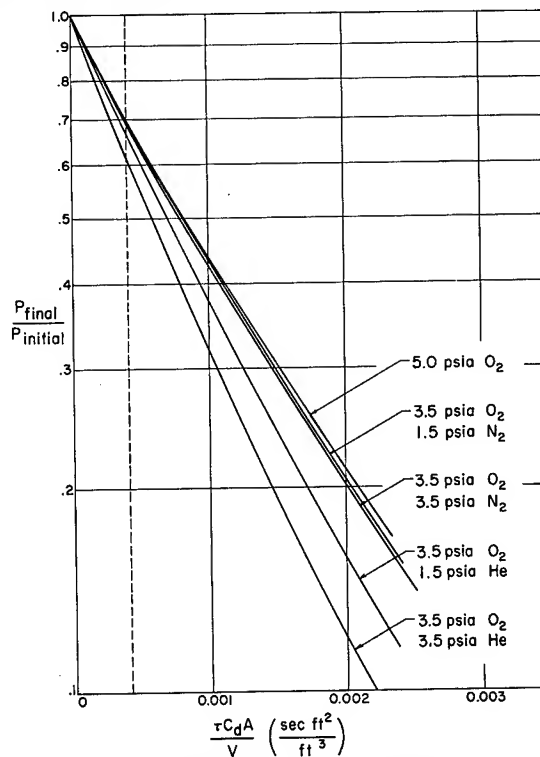
$$\tau = \frac{0.00575 \times 770}{\frac{\pi \times (0.25)^2}{144}} = 325 \text{ sec}$$

Figure 12-9

The Sensitivity of Rapid Decompression to Composition of Atmosphere
(After Roth (103), adapted from Boeing (17))



a. Isothermal Decompression



b. Isentropic Decompression

The time to reach minimum tolerable partial pressure of P_{O_2} can be calculated by the factors of Figure 12-1. This reduces the available time considerably. (Table 12-10 represents the time in minutes required to meet minimum tolerable total pressures as determined by minimal P_{O_2} levels for 1/2 inch and 3/4 inch holes under isothermal and isentropic conditions with five proposed atmospheres.) It can be seen that in all cases, the oxygen-nitrogen mixture at 7 psia takes the longest times and 100 percent oxygen takes the shortest time to reach the critical condition. The larger the hole, the less the absolute difference between mixtures. Pure oxygen gives more than twice the time of useful work than do the other gas mixtures at 5 psia. The lower the partial pressure of inert gas, the less time required to reach both endpoints and the greater the difference between the two criteria. From the point of view of the human subject, Table 12-10 presents the more valid endpoint than just pressure. At equivalent composition and pressure, nitrogen has a slight advantage over helium.

Table 12-10
Decompression Time to Minimum Tolerable Total Pressure as Determined by Minimum Acceptable P_{O_2} ; (Cabin Volume = 770 Ft³; Orifice Coefficient = 1)
(After Boeing⁽¹⁷⁾)

Leak mode	3.5 psia O ₂ 3.5 psia N ₂	3.5 psia O ₂ 3.5 psia He	3.5 psia O ₂ 1.5 psia N ₂	3.5 psia O ₂ 1.5 psia He	5.0 psia O ₂
	7.0 psia	7.0 psia	5.0 psia	5.0 psia	
Decompression time, min					
Isothermal - 1/2-inch hole.....	6.17	4.72	2.25	1.93	5.42
Isentropic - 1/2-inch hole.....	4.54	3.22	1.62	1.35	3.95
Isothermal - 3/4-inch hole.....	2.75	2.1	1.0	.86	2.41
Isentropic - 3/4-inch hole.....	2.03	1.42	.72	.59	1.75

There may be operational significance between the maximally divergent times of 6 minutes and 2 minutes for the 1/2-inch hole with isothermal flow. If the mission requires at least 6 minutes for donning an emergency suit in a high-risk phase, this difference may well be critical in the selection. The probability of a penetration producing such a hole size is obviously a major mission-specific factor to be considered.

There are several other minor considerations in the area of fast-flow systems. These are the maximum airlock dumping and repressurization times during extravehicular operations and the maximum rate of cabin pressure dumping during fire emergencies. The dumping of airlock and cabin would, of course, follow the more isentropic type of flow. The faster the flow through the maximum orifice available, the more advantageous the gas mixture. One would therefore have to weight the advantage of having a more rapid dumping capability for a suited crew against a less-rapid emergency dumping after accidental puncture with an unsuited crew.

The repressurization of an airlock from a vacuum to the pressure of the main compartment is most rapidly accomplished by opening a valve between the two chambers. In most cases, the pressure and temperature of the main compartment is maintained constant by the gas feed system and the compression will be close to isothermal because of the great flow turbulence in the

airlock. The flow across the valve starts off as a supercritical pressure ratio and then becomes subcritical when

$$P_c/P_{lk} = \left(\frac{2}{\gamma+1} - \frac{\gamma}{\gamma-1} \right) \quad (4)$$

where P_c = cabin pressure

P_{lk} = lock pressure

The approximate time required to recompress a lock isothermally from vacuum, τ_t , can be determined for air of $\gamma = 1.4$ by the equation

$$\tau_t = \frac{V}{130 C_d A} \sqrt{\frac{m}{T_{lk}}} \quad (5)$$

where m = average molecular weight of the gas

T_{lk} = is the absolute temperature of the lock

γ = ratio of specific heats.

This aspect of a space mission will be critical only when a crewman must be retrieved most rapidly through a lock to a cabin. Since the relatively small volume of the lock suggests that the minimum time for recompression will not in any practical way limit the survival potential of the crewman, the effect of atmospheric composition should have little practical effect on the survival. The difference in time, measured by seconds, which will be given the entering crewman by an optimum gas mixture does not appear to warrant a thorough analysis of the problem in the present context. Such an analysis is available (30). That the gas-specific factor will probably not be critical is indicated by their calculation from equation (5) that a lock of 40 ft³ can be isothermally pressurized by air to 99 percent of the main compartment pressure through a valve of only 0.58 in.² in 30 seconds. Doubling the area of the valve can reduce this time to about 15 seconds. Since the time required is proportional to the square root of the molecular weight, substitution of air (molecular weight = 29) by the proposed mixture of lowest molecular weight, helium-oxygen mixture at 7 psia (molecular weight = 18), will reduce minimum compression time by only a few seconds. For larger lock systems, the number of seconds to be saved will increase as will the physiological significance of the savings. However, the valve size can be increased to meet this demand in a large lock.

One must also consider the airlock pumping weight penalties. The airlock may be pumped into a separate storage tank or into the main compartment. The effect of atmosphere composition on this penalty is currently under study (109). Data are also available on a new elastic recovery principle in the design of airlocks (23).

One must be aware of the time of useful consciousness following decompressions lasting several seconds. Following rapid decompression to an ambient P_{O_2} equivalent to altitudes of about 25,000 feet or above, consciousness is rapidly lost (84, 97).

Figure 12-11 represents the mean and minimum times of useful consciousness available when air or 100% oxygen are being breathed at sea level pressures before and during the decompression.

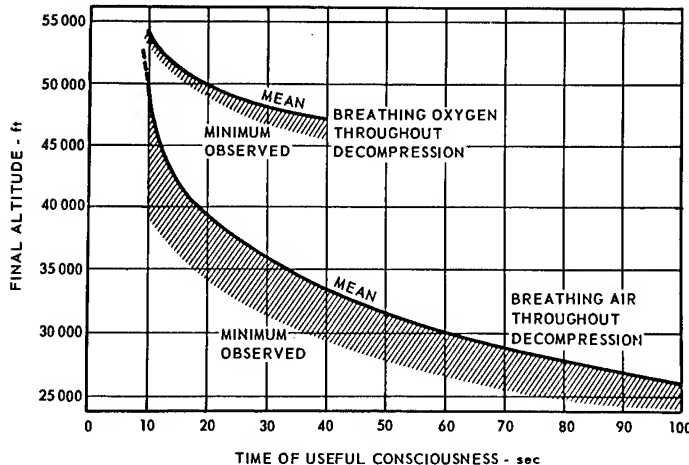


Figure 12-11

Minimum and Mean "Times of Useful Consciousness" Following Rapid Decompression of Humans Who Are Breathing Either Air or Oxygen Throughout Decompression

(After Blockley and Hanifan⁽¹⁶⁾, after data of Luft⁽⁸³⁾ and others

The "time of useful consciousness" becomes shorter with increasing altitude until a minimum time is reached. This minimum is reached at about 46,000 feet (106 mm Hg or 2.04 psia) when air is breathed throughout the decompression, or, about 52,000 feet (79 mm Hg or 1.53 psia) when oxygen is breathed throughout the decompression. There is a "critical time of exposure" during which an individual must breathe an adequate partial pressure of oxygen if continuous consciousness is to be preserved. This time also reaches a minimum with increasing altitude (3, 24, 83). Oxygen must be given within 7 secs in order to preserve continuous consciousness in subjects decompressed from 8,000 feet (564 mm Hg or 10.91 psia) to 40,000 feet (141 mm Hg or 2.72 psia) in 2.5 sec. The "critical time of exposure" should not exceed 5 to 6 sec in rapid decompressions (2 sec) to altitudes above 52,000 feet (79 mm Hg or 1.53 psia). Specific symptoms resulting from oxygen lack or hypoxia may be found in Oxygen-CO₂-Energy (No. 10).

Treatment of hypoxic emergencies resulting from exposure to vacuum is covered below under ebullism (26, 99).

Lung Damage from Explosive Decompression

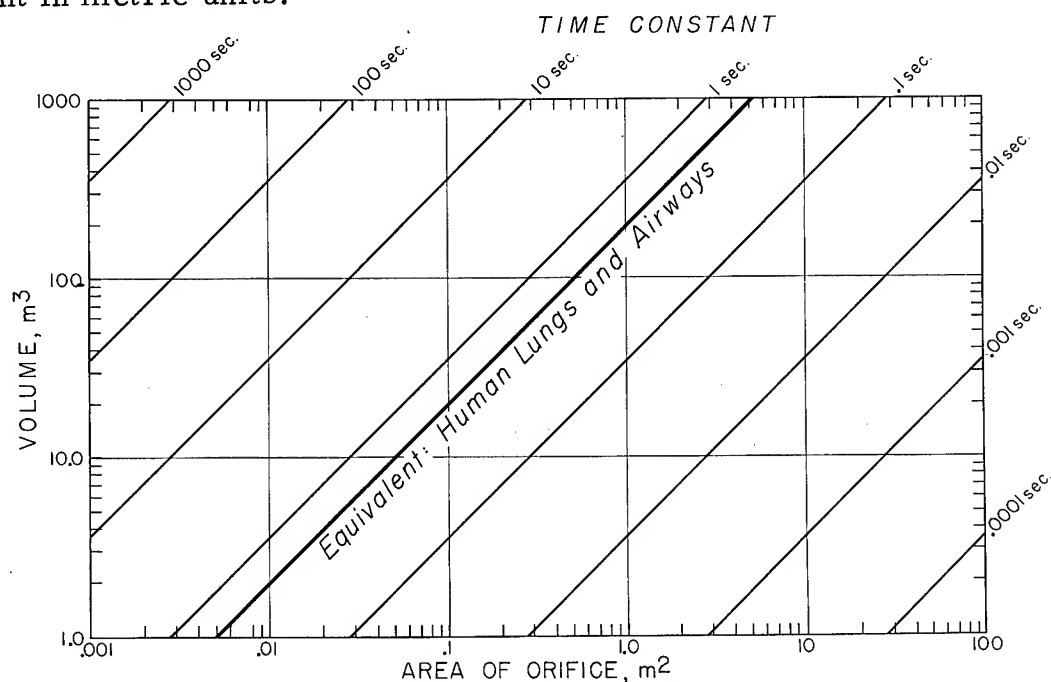
Sudden disruption of a cabin wall or a space suit may decompress an astronaut or test subject rapidly enough to damage his lungs. The problem has been recently summarized by two reviews from which much of the following material is taken (79, 99).

The severity of mechanical effects on the body in rapid decompression is dependent on the change in absolute pressure, the ratio of initial to final pressure, and the rate of decompression. The latter can be defined rather precisely on the basis of physical theory if the pressure conditions, the volume of the cabin or suit and the size of the aperture are known or can be assumed

(46, 48, 51, 90). In the presence of humidity, the decompression is neither an adiabatic nor an isothermal process, but is polytropic in character. The rate of flow through the orifice may be of subsonic or sonic velocity, according to the pressure ratio across the orifice. If the critical ratio of approximately 2 to 1 is exceeded, the escape flow will be constant at the speed of sound regardless of how high the pressure head may be. The initial rate of change in pressure is determined by the absolute magnitude of the initial cabin pressure. For all practical purposes, the complex factors that define the decompression transient can be resolved into two principal determinants (51). The first of these, which sets the absolute time scale of decompression, will be referred to as the time constant (t_c)

$$t_c = \frac{V (m^3)}{A (m^2) \cdot C (m/sec)} \quad (6)$$

It is defined by the ratio between cabin volume (V) and the effective area of the decompression orifice (A). The velocity of sound (C) is introduced as a characteristic of flow that eliminates the effect of density. It will be seen that t_c must appear in units of time, all other units canceling out. The time constant is independent of pressure. The chart in Figure 12-12 is a graphic solution of equation (6) relating cabin volume and effective orifice to the time constant in metric units.



The volume of the pressure cabin relative to the effective area of the decompression orifice determines the time constant of decompression. For the respiratory tract this depends on the lung volume and the flow resistance of the airways at the time of decompression.

Figure 12-12
Time Constants of Explosive Decompression
(After Luft(79))

The second determinant is the pressure factor (P_1) derived for a polytropic process under subsonic or sonic conditions of flow. P_1 is a function of the initial cabin pressure (P_i) and the final pressure of equilibrium with the environment (P_f), and is independent of the absolute pressure (51).

$$P_1 = f \frac{P_i}{P_f} \quad (7)$$

The values for P_1 can be read for any desired pressure ratio from the curve in 12-13a. The total duration of decompression (t_d) is the product of the time constant (t_c) and the pressure factor P_1 .

$$t_d = t_c \cdot P_1 \quad (8)$$

The relationships expressed in equations (6) and (8), which have been verified in numerous experiments, are convenient for estimating the decompression time on the basis of cabin volume and the configuration of windows, doors, or canopy for various cabin pressures at altitude. Similarly, the volume to orifice ratio and the time constant of any decompression situation can be estimated if the elapsed time of decompression and the pressure ratio P_i/P_f are known.

Under vacuum conditions, the duration of decompression becomes extremely long because the final equalization of pressure is very slow. Under these circumstances, the initial part of the transient where the rate of decompression is constant (constant rate time) is more meaningful, as far as biological effects are concerned, than the total duration of decompression. As shown on Figure 12-13b the line of initial rate of change is extended until it intersects the ambient pressure P_{ao} . The point of intersection marks a time which is evidently related to the initial rate of pressure change and the pressure difference. This "constant rate time" (t_{cr}) can be calculated from the time constant (t_c) and another pressure factor (P_3) which may be read from the curve so designated on Figure 12-13a for the appropriate decompression ratio:

$$t_{cr} = t_c \cdot P_3 \quad (9)$$

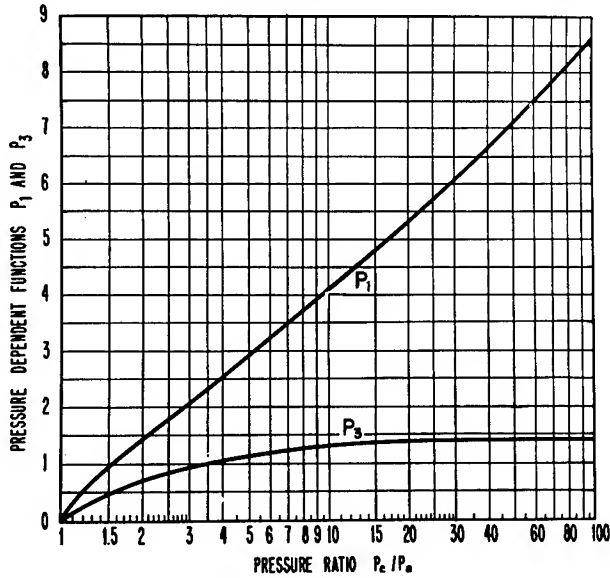
If an individual were decompressed from an initial cabin pressure, P_i , to a final pressure, P_f , at altitude with closed airways in the absence of any change in his lung volume, the pressure in his lungs, P_L , would remain equal to P_i , and the pressure gradient, ΔP_L , sustained by his lungs and chest would be equal to the total pressure difference of decompression.

$$\Delta P_L = P_L - P_f = P_i - P_f \quad (10)$$

On the other hand, if the gas in his lungs could expand without constraint, as in a frictionless piston, its volume would increase from V_i to V_f until P_L became equal to P_f . The relative gas expansion, RGE, assuming isothermal conditions with water vapor pressure at 47 mm Hg would be (78)

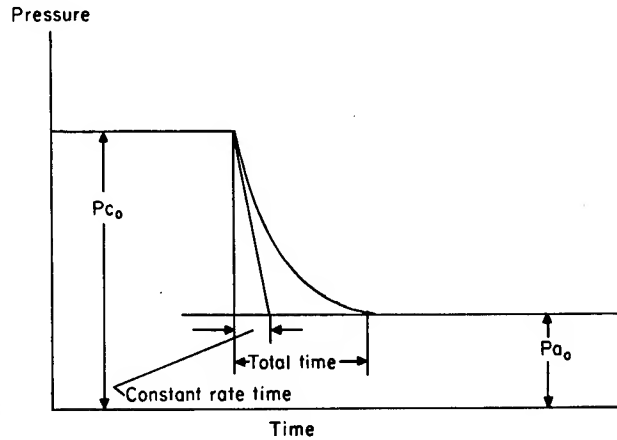
Figure 12-13

Correction Factors for Explosive Decompression to Low Pressures



- a. The Pressure Function P_1 for the Total Time of Decompression and for the "Constant Rate Time (P_3) as Derived from the Pressure Ratio (P_c/P_a) or (P_i/P_f)

(After Bancroft (6))



- b. Definition of Constant Rate Time t_R

(After Haber and Clamann (51))

$$\frac{V_f}{V_i} = \frac{P_i - 47}{P_f - 47} = \text{RGE} \quad (11)$$

The lung is neither a rigid container nor a frictionless piston, but an elastic container with limited capacity. The pressure difference across the lungs and chest will tend to expand their contents toward a maximal intact volume, V_{\max} , or beyond. The virtual pressure in the lungs, P_L , at the moment in which the maximal intact volume is reached, is estimated by modifying equation (11) accordingly.

$$\frac{V_{\max}}{V_i} = \frac{P_i - 47}{P_L - 47} \quad (12)$$

and solving for P_L ,

$$P_L = \frac{V_i}{V_{\max}} (P_i - 47) + 47 \quad (13)$$

The pressure difference, ΔP_L , is found by substituting equation (13) for P_L into equation (10):

$$\Delta P_L = \frac{V_i}{V_{\max}} (P_i - 47) + 47 - P_f \quad (14)$$

It is apparent from equation (14) that when the initial and final pressures of decompression are given, the volume of gas trapped in the lungs relative to the total capacity is the factor determining the critical pressure gradient. According to the animal experiments and human experience, rupture of the lungs is liable to occur when ΔP_L exceeds 80 mm Hg (64, 79, 95, 106). Counterpressure exerted by the chest cage when the lungs are passively distended to their full capacity (relaxation pressure) explains the fact that excised lungs disrupt at a pressure of only 50 mm Hg. Furthermore, when an animal's trunk is bound with inelastic fabric or laid in a plaster cast, tracheal pressures as high as 180 mm Hg are tolerated without discernible damage to the lungs (95). These findings point to the fact that high pressure in the lungs is dangerous only if it is permitted to expand pulmonary tissue beyond its tensile limits. In the act of coughing, intrapulmonic pressures of more than 150 mm Hg are tolerated frequently without untoward effects, in the absence of pulmonary pathology. In contrast to the process of passive inflation, the pressure pulse of a cough is the result of active muscular effort, which actually reduces lung volume by compressing its gas content.

By means of equation (14) one can estimate whether the critical pressure for ΔP_L will be exceeded for decompressions of known initial and final pressure with closed airways. If ΔP_L , calculated from equation (14) is less than 30 mm Hg, then the decompression in question would not expand the lungs from V_i to V_{\max} and, therefore, would not be dangerous. The initial and final pressures for which the critical overpressures of 80 mm Hg would be reached in the lungs must be calculated for three different lungs volumes: full expiration (Ex), full inspiration (In), and for the normal respiratory position around the midlung volume. The probability is very high that inadvertent decompression would occur during normal respiratory excursions, and it is reasonable to assume a value of 0.55 for V_i/V_{\max} in equation (14) for most instances.

Evaluation of damage risk to the lung during space operations in the case of breathholding has been reviewed using these relationships. The pressure gradient which exists across human lungs and passively distended chest wall during an "explosive" decompression to a vacuum occurring while respiratory passages were closed was calculated for internal pressures of 7 psia and 5 psia which are currently considered for spacecraft and 3.7 psia for space suits. Three different lung volumes prior to decompression are considered: full inspiration ($V_i/V_{\max} = 1.0$), the normal end expiratory position ($V_i/V_{\max} = 0.55$), and full expiration ($V_i/V_{\max} = 0.25$). These data are presented in Table 12-14. It is interesting to note that all pressure gradients under these conditions are over the previously stated critical level of about 80 mm Hg. Therefore, an "explosive" decompression in a vacuum while respiratory passages are closed is considered a very great hazard from the standpoint of serious lung injury.

Table 12-14

Pressure Gradients Across an Astronaut's Lungs and Passively Distended Chest During "Explosive" Decompression in Space with Closed Glottis

(After Busby⁽²⁶⁾, from the unpublished calculations of Luft

Pressure gradients ΔP_L calculated for different ambient atmospheric pressures. (P_i) and lung volumes (V_i) prior to decompression to a vacuum ($P_f = 0$).

$\frac{V_i}{V_{\max}}$	ΔP_L at $P_i = 7.0$ psia (362 mm Hg)	ΔP_L at $P_i = 5.0$ psia (259 mm Hg)	ΔP_L at $P_i = 3.7$ psia (191 mm Hg)
1.0	362 mm Hg	259 mm Hg	191 mm Hg
0.55	220 mm Hg	164 mm Hg	121 mm Hg
0.25	126 mm Hg	100 mm Hg	83 mm Hg

In explosive decompression during normal respiration, the case is more complex (79, 81, 82). If the time characteristic of the human lung and airway is greater than the time characteristic of the pressure suit or cabin in which an individual is confined during the decompression, a transient differential pressure will build up between the lungs and ambient atmosphere. This is illustrated diagrammatically in Figure 12-15.

The heavy line in Figure 12-12 represents the time characteristic of the human lung with open glottis on a background of the volume-to-orifice ratio. There is a critical V/A ratio of the cabin or suit relative to this ratio of

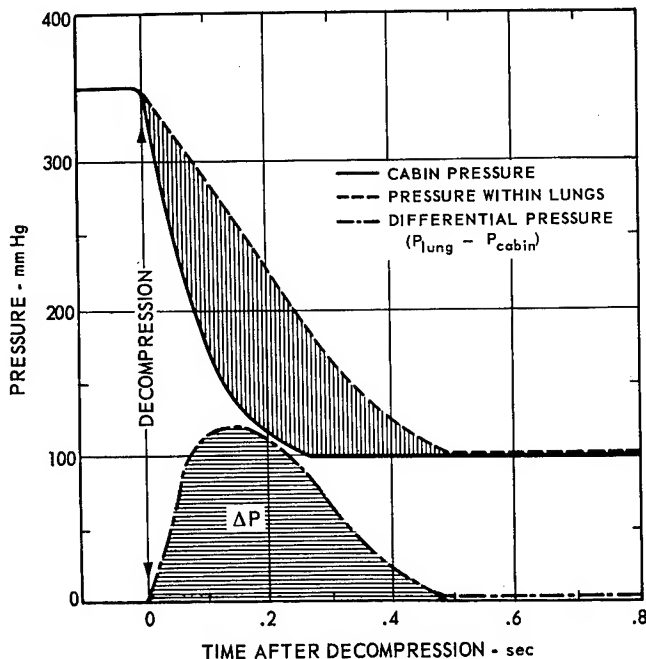


Figure 12-15

Time Characteristics of Overpressure in the Lungs

(Adapted from Luft⁽⁸⁰⁾ by Billings and Roth⁽¹⁵⁾)

the human respiratory tract determining the threshold for injury or death. Another factor that influences the transthoracic pressure transient is the pressure ratio (P_i/P_f). It can be shown mathematically and empirically that if decompression takes place over the same pressure difference, but at higher altitude where the pressure ratio is greater, the amplitude of pressure differential of Figure 12-15 remains the same, but the duration of the transient is longer (79, 81). This means that the area under the differential pressure curve which represents the impulse in terms of

$$\frac{\text{force (dyne) x time (sec)}}{\text{area (cm}^2\text{)}} \quad (15)$$

is a function of the decompression ratio. Unfortunately, there are no data correlating lung damage directly with impulse. The shape and duration of a blast wave is certainly a factor in predicting damage from overpressure (22, 98).

The conclusions to be drawn from these model analyses can be summarized as follows: 1) The maximal possible amplitude of the transmural pressure in the lung model is equal to the pressure difference of decompression ($P_i - P_f$). 2) The fraction of the total pressure difference effective in the lung is dependent on the V/A ratio in the lung to that of the suit or cabin. 3) The pressure ratio of decompression (P_i/P_f) determines the force x time integral or impulse for any given amplitude of the transthoracic pressure transient and, therefore, the duration of a critical overpressure.

In addition to the perturbing effect of water vapor in the lungs, the most important shortcoming of a rigid model is that it fails to simulate the elastic expansion of lungs and chest in decompression, as would occur according to equation (14) for isothermic conditions, with a corresponding drop of pulmonary pressure. In dogs, expansion is not apparent before 10 msec (117). In man, the time lag is probably even greater, since it is a function of the mechanical impedance of the lungs and chest which increases with body size (41, 106).

According to the cinematographic data, decompression of the lungs takes place in three phases. The first is under essentially isometric conditions with no change in volume, owing to the inertia of the system. The highest transthoracic pressures are probably attained during this phase in which the lungs are comparable to a rigid bottle. In the second phase, the pressure is attenuated due to expansion of the chest and also to the continuing escape of gas through the airways. In the third phase of maximal expansion, the conditions are again isometric until the overpressure is dissipated and the lung volume decreases. Structural damage is conceivable during the first and second phases, when the peak pressure creates powerful dynamic forces opposed by the inertia of the system. In a medium consisting of components with widely different densities, such as the organs in the chest, differences in acceleration under the impulsive pressure loading could result in shearing and spalling lesions similar to those encountered in blast injuries in the vicinity of explosions (29, 107). During the third phase of maximal expansion of the lungs, the mechanism of injury would be comparable to that assumed for decompression with closed airways, namely, rupture of tissues at the limits

of their tensile strength. Penetration of gas bubbles into the bloodstream most likely take place when the lungs are fully expanded and a high gradient is created between the intrapulmonic pressure and that in the pulmonary veins and left atrium (106). Air embolism may be facilitated at this time at the sites of lung damaged in the first two phases of decompression.

Experimental substantiation of this model is difficult. Experimental procedures often do not exclude the influence of hypoxia and decompression sickness or of boiling phenomena on the experimental animals; and more often no effort is made to discriminate between the many factors involved by keeping one or more of these constant. Nevertheless, certain notable relationships emerge that support the following concept. There can be no doubt that the rate of decompression is a decisive variable in the mortality of animals (79). This holds true from initial pressures of 1 atm., at differential pressures of greater than 630 mm Hg (0.83 atm.), and decompression times from 0.630 to 0.0014 second. Since the decompression time is also influenced by the pressure ratio of decompression which differs considerably, the V/A ratio is preferable as a characteristic of the rate of decompression. In all tests where V/A was $15 \text{ m}^3 \text{ per m}^2$ or more, all animals survived. A significant number of fatalities appears when V/A was $3.3 \text{ m}^3 \text{ per m}^2$, and the LD_{50} corresponded to a V/A of 1.1 to $1.2 \text{ m}^3 \text{ per m}^2$. In the only investigation where 100 percent mortality was produced, a special decompression device with a V/A of $.12 \text{ m}^3 \text{ per m}^2$, was used (72). In decompression of such extreme rapidity, there can be very little escape of gas from the lungs before the full pressure gradient becomes effective and the lungs and chest are overdistended with a pressure load practically as great as if the airways had been completely closed. If this were true, one would expect some fatal injuries to occur under the same pressure conditions as found in decompression with closed airways. According to equation (14) solved for decompression from sea level with closed airways at midlung volume, a critical ΔP_L of 80 mm Hg can be predicted when the final pressure is lower than 359 mm Hg or 0.47 atm. When rats were exposed to increasing pressure differences from an initial pressure of 735 mm Hg with a V/A of .12, an increasing number of fatalities were observed whenever the final pressure was less than 368 mm Hg (0.48 atm) (72). Conversely, the fastest decompressions were innocuous when this pressure range was not exceeded. Convincing evidence that the mechanism of fatal injury is overdistention of the lungs and not the pressure pulse per se was obtained by exposing animals with an artificial pneumothorax to extreme decompression and finding less trauma than in the untreated (72).

With slower rates of decompression and open airways only a fraction of the total gradient of decompression will come to bear upon the lungs as more gas has had time to escape before they are fully distended. As pointed out for the rigid model above, the amplitude of the pressure transient in the lungs is dependent on the V/A ratio of the lungs and airways relative to that of the suit or cabin system. From intrathoracic pressure transients recorded in man it has been estimated that the human lungs and airways correspond to a V/A of approximately $180 \text{ m}^3 \text{ per m}^2$. For dogs, this V/A ratio is 100 (117). This indicates that the dogs may tolerate somewhat lower cabin V/A ratios than humans. However, this difference may well be due to the different experimental techniques used to obtain the values. These figures provide a cue for safety limits in the permissible rate of decompression, since

decompression to unlimited altitudes would not give rise to disruption of the lungs if the V/A of the cabin were no less than the human equivalent.

Experience with human exposure to decompression at low cabin V/A ratios is very limited (12, 28, 39, 40, 62, 76, 79, 99, 113). Well-documented, danger-zone decompressions with open glottis have been limited to those recorded in Table 12-16. It can be seen that only the first exposure

Table 12-16
Rapid Decompression Tolerated by Man
(After Luft⁽⁷⁹⁾)

Ref.	No.	Altitude, feet	$P_{i,*}$ mm Hg	$P_{i,\dagger}$ mm Hg	$P_i - P_t$ mm Hg	P_i/P_t	Time, sec	V/A†	$\Delta P_{L,\S}$ mm Hg
Sweeney	113	27,000-45,000	253	112	141	2.23	.005	1.0	48
Sweeney	6	8,000-35,000	565	179	386	3.16	.090	13.4	153
Döring	40	9,800-49,100	526	90	436	5.83	.230	23.0	220

^a ΔP_L is the overpressure which would occur in the lungs if the airways were closed at midlung volume; critical pressure is 80 mm Hg (Eq. 14).

of Sweeney would have had a cabin V/A ratio ($1 \text{ m}^3/\text{m}^2$) well within the expected lethal range. Even under closed airways at midrespiratory volume, the pressure ratio P_i/P_f would have been small enough in the first case with low V/A ratio to have prevented the critical overpressure of 80 mm Hg from being reached (79).

Figure 12-17 is a summary curve which represents a rough evaluation

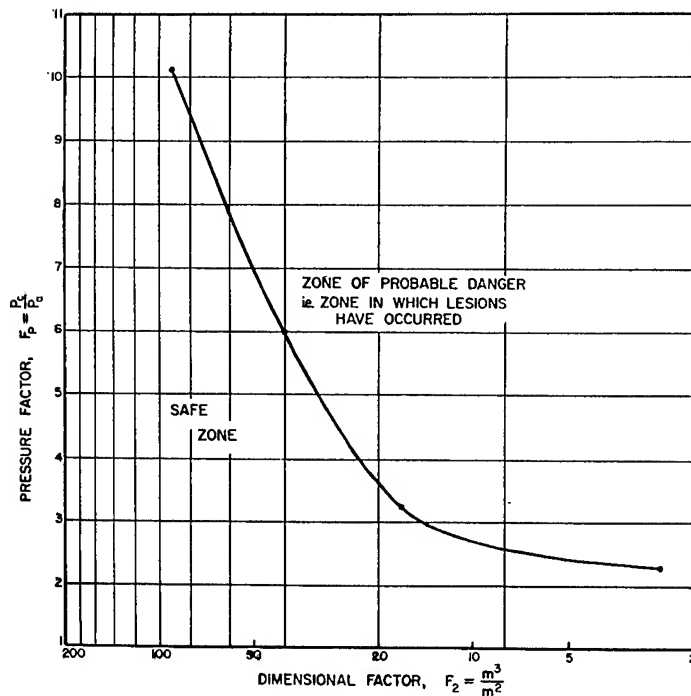


Figure 12-17

Curve Derived from Human and Animal Data Defining the Zones of Safety and Probable Danger in Explosive Decompression with Open Glottis (See text)

(After Fryer⁽²⁸⁾ from the data of Violette⁽¹¹⁷⁾)

of the relative dimensional and pressure-ratio factors defining the zone of possible injury under glottis-open conditions. The curve does have some shortcomings. For instance, it is doubtful whether it is permissible to plot animal and human data on a common figure. Again, the degree and actual aetiology of damage in animals in many series of experiments is not fully known. Comparison with animal data (72) and the data of Table 12-16 shows that the curve is conservative enough for a first approximation of the safe zone. Lack of direct data regarding V/A ratios of animal experiments makes the degree of conservatism difficult to assess. In those humans where lung damage was sustained, there is inadequate information about the degree of breathholding and the fraction of vital capacity during exposure. These factors preclude adequate evaluation of the zone above the curve in Figure 12-17, especially in the pertinent zone of high P_c/P_a ratios of vacuum exposure. Another factor controlling the extrapolation of animal data to humans is the relative inertia of the chest wall during phase 2 of the decompression. The time required to move the chest wall should roughly scale directly as the one-third power of the mass of the animal (21). This will determine the rate of application of the tensile forces on the critical lung structures. This factor has not been considered in the above discussion.

In decompression of a space cabin, the composition of atmosphere is a factor in lung damage. For the present, the use of gas other than 100% oxygen is most unlikely in extravehicular suit assemblies. However, there is a possibility that improvement in joint design may permit development of hard suits operating under relatively high pressures with inert gas mixtures. The flow of gas through the respiratory tract is a critical factor during "explosive" decompression (103). A rigid analysis of the flow factor has been made using a mathematical model of the fluid-mechanical response of the thoracoabdominal system to blast overpressure and "explosive" decompression (22). An analysis of the gas-dependent factors in this model leads to the conclusion that the rate of pressure change in the lung with respect to ambient $\left(\frac{dP}{dt}\right)_{t=0}$ is a function of the product of the reciprocal of the square root of the average molecular weight of the gas M and a gas-flow factor involving the specific heat ratio γ . This relationship is shown in the following equation

$$\left(\frac{dP}{dt}\right)_{t=0} \sim \frac{1}{M^{1/2}} \left(\gamma \left[\gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{1/2} \right) \quad (16)$$

The lower the rate of pressure change in the lung with respect to ambient, the more dangerous is the atmosphere. This same relationship would define the hazard from external blast overpressure. For isothermal processes, the value of $\gamma = 1$ can be used. For adiabatic processes the values of γ are obtained from the C_p/C_v ratios (103). The ratios for the inert gases lie in the 1.67 range, except for nitrogen at 1.4. The value for oxygen is 1.4.

It is still not absolutely clear whether adiabatic or isothermal processes predominate in the lung in "explosive" decompression or blast overpressure.

The rapidity of the process suggests adiabatic conditions. It must be remembered, however, that the alveoli of the lung present a large surface for heat exchange and high humidity. This would allow for rapid condensation of water vapor to counteract the adiabatic cooling. The temperature change in the lung during "explosive" decompression has been found to be minimal (58). Sensor lag obviously complicates the measurement to an unknown degree. A value of $\gamma = 1.2$ for air has been used as a polytropic compromise in an unknown situation (22) but it is felt that the isothermal process probably predominates (45). In the analysis of the space-cabin situation, calculations were made for the currently proposed environment of 50 percent inert gas and 50 percent oxygen. Both the isothermal and 50 percent isothermal-50 percent adiabatic specific heat ratios are presented in Table 18. For the isothermal condition, $\gamma = 1$. Table 12-18 represents the calculations of

Table 12-18

Relative "Explosive" Decompression and Blast Overpressure Hazards from Atmospheres at 7 Psia with 50 Percent Inert Gas and 50 Percent Oxygen

(After Roth (103))

Factor	Gas mixture in cabin						
	He-O ₂	Ne-O ₂	Ar-O ₂	Kr-O ₂	Xe-O ₂	N ₂ -O ₂	O ₂
$1/M^{1/2}$	0.34	0.20	0.17	0.15	0.13	0.18	0.18
γ (50 percent adiabatic).....	1.25	1.25	1.25	1.25	1.25	1.20	1.20
Isothermal expansion ($\gamma = 1$) $\left(\frac{dP}{dt}\right)_{t=0}$.....	.34	.20	.17	.15	.13	.18	.18
Relative hazard index (N ₂ -O ₂ = 1).....	.53	.90	1.1	1.2	1.4	1.0	1.0
Polytropic expansion (50 percent adiabatic) $\left(\frac{dP}{dt}\right)_{t=0}$.....	.26	.15	.13	.11	.10	.13	.13
Relative hazard index (N ₂ -O ₂ = 1).....	.50	.87	1.0	1.2	1.3	1.0	1.0

$\left(\frac{dP}{dt}\right)_{t=0}$ for these gas mixtures and the relative hazard index with nitrogen-oxygen = 1. The relative hazard index is calculated from the reciprocal of the $\left(\frac{dP}{dt}\right)_{t=0}$ factor. The nitrogen-oxygen and the 100 percent oxygen (7 psi) atmospheres would have the same degree of hazard. It can be seen that the major gas factor is $1/M^{1/2}$. The thermodynamic nature of the expansion has little effect on the relative hazard of the inert gas. Helium-oxygen appears to be about 0.5 as hazardous as nitrogen-oxygen or 100 percent oxygen; neon-oxygen appears to be about 0.9 as hazardous. The relative degree of hazard then increases with increasing molecular weight for the other gases. It should be pointed out that these are the maximum differences expected. Most second-order factors would probably tend to decrease the relative molecular-weight dependence. For example, the rate of gas escaping from the cabin is also dependent upon molecular weight. However, when one reviews the cabin V/A ratios required for lethality in animals, it is evident that the cabin

pressure will have essentially reached ambient well before the flow of gas out of the respiratory tree has ceased. Any overlap of these flows would reduce the dependence upon molecular weight. Therefore, a prediction can be made that the smaller the hole, the less gas-dependent is the hazard. The practical significance of gas-specific factors in lung damage is open to question.

Another variable to be considered in evaluation of the hazard of decompression is the presence of oxygen mask or respiratory equipment which may superimpose an artificial "glottis" over the normal one and increase the effective V/A ratio of the subject (82). This should not be a consideration in current full pressure suits where large plastic bubble helmets surround the facial area.

The several mathematical models of the thorax-abdominal system for evaluating the hazards of air blast overpressure and explosive decompression damage to the lungs require more empirical study for confirmation of their validity under the several variables of the current problem (22, 73). When fully validated, these models could be used to give a finer prediction of the hazards under the specific internal pressure profiles presented by disrupting cabins and space suit assemblies.

From the above discussion of critical V/A ratios, it can be calculated that with glottis open, an astronaut in a 50 cu ft cabin of Project Mercury would have to sustain an acute disruption of at least 1 sq foot of cabin wall to receive damage to a normal lung. In the case of suit disruption, the problem is more complex (99). Except for joint and helmet areas, the laminated fabric of the soft suit and metal shell of the hard suit are reportedly safe from acute disruption. Verbal reports from the engineers interviewed suggest that the "fail-safe" nature of neck seal and probably the wrist, thigh, and ankle seals, relegate the chances of acute disruption to a very low category. The waist seal of the hard suit is the most vulnerable site of disruption. The laminated fabric lining the bellows systems reduces their vulnerability to catastrophic disruption.

The time characteristic anticipated from disruption of soft and hard suit seals is shown on Table 12-19. The residual suit volumes were calculated from frontal areas of the suit sections. Orifices were of annular type calculated by subtracting from the cross section area of the suit at the disrupted seals, the cross section of the body segment enclosed. From Table 12-19 and the data presented above, it can be concluded that acute catastrophic disruption of the neck and wrist seals of the soft and hard suits and disruption of the neck, thigh, and ankle seals of the hard suit may well lead to lung damage in a previously normal, suited subject in a vacuum chamber or in space. This is true even for open-glottis conditions. The hazard is intensified if the glottis is closed and breath is held. Disruption of a glove finger in both suits and the portable life support (PLSS) umbilical in the hard suit would probably not lead to lung damage if the glottis were open, but may lead to difficulty if the breath were held during the decompression. Disruption of the chamber umbilical in the hard and soft suits and PLSS umbilical in the soft suit, particularly at the entrance ports to the suit, could possibly lead to lung damage under open-glottis conditions. However, the case is less clear

Table 12-19

Time Characteristics of Explosive Decompression Predicted for Acute Disruption
of Space Suits During EVA and in Test Chambers (See text)

(After Roth (99))

<u>Soft Suits</u>	Residual Suit Volume (cc)	Orifice Area (cm ²)	V/A Ratio (meters)	t _c (sec) (Fig. 12-13)	P3	t _{cr} (sec)
Neck Seal (PLSS)	26,000	295	0.88	0.0025	1.45	0.0036
Wrist Seal (PLSS)	28,000	60	4.67	0.0134	1.45	0.019
Chamber umbilical hose	25,500	7.9	32.3	0.093	1.45	0.14
PLSS umbilical hose	28,000	2.8	100.	0.286	1.45	0.41
Fingers (PLSS)	28,000	1.2	233.	0.670	1.45	0.97
<u>Hard Suits</u>						
Waist Seal (PLSS)	35,200	810	0.435	0.00125	1.45	0.0018
Neck Seal (PLSS)	70,600	561	1.25	0.00359	1.45	0.0052
Thigh (PLSS)	64,000	177	3.6	0.0104	1.45	0.015
Ankle (PLSS)	75,000	168	4.46	0.0128	1.45	0.019
Wrist Seal (PLSS)	75,000	54	13.9	0.0399	1.45	0.058
Chamber umbilical hose	71,000	7.9	89.8	0.255	1.45	0.370
PLSS umbilical hose	75,000	2.8	268.	0.77	1.45	1.1
Fingers (PLSS)	75,000	1.2	620.	1.78	1.45	2.6

than the previous one. Disruption of the umbilical hoses at a distance from the entrance port would lower the probability of damage (99, 114). It is clear from this analysis that all seal areas should be designed for slow propagation of disruptive processes. The advisability of preparing therapeutic devices and facilities for handling explosive decompression emergencies would, strictly speaking, depend on the actual reliability of the suit seals under question, and the assumed degree of conservatism used in extrapolating from animal data obtained at pressure regimes different from the case in question. However, these uncertainties suggest that accidents should be anticipated and plans made accordingly.

During the second phase of maximal expansion of the lungs and chest wall, disruption of the tissues would occur as their tensile strength is exceeded. This would also occur during decompression with closed airways. These structural defects lead to pulmonary hemorrhage and edema as well as to pneumoperitoneum and pneumothorax. During the third phase of maximal expansion, penetration of bubbles into the blood stream takes place as a high pressure gradient is formed between the alveoli and the pulmonary veins. Gas emboli enter the blood stream and pass to the arterial circulation. Such embolization may continue to occur upon inspiration for some time after the decompression.

Death is usually caused by hemorrhage from the disrupted lung or by introduction of gas emboli into the venous side of the pulmonary circulation and subsequent infarction of critical sites in the systemic circulation. Exposure to the vacuum for several minutes can lead to further lung damage and to the ebullism syndrome (see below). The pathological physiology and optimum treatment of these syndromes has been recently reviewed (26, 99). All human accidents and the single fatality are reviewed in detail.

One factor which must be considered in the selection of astronauts or test subjects is prior pathology in the lungs. Plugs of mucus in the bronchioles reduce the local V/A ratio and increase the distal transalveolar pressure impulse during the decompression. Such plugs were found in the one reported human death after explosive decompression (112). Those factors which weaken the alveolar walls would increase the hazard of exposure. The same conditions predisposing to spontaneous pneumothorax would be expected to increase the chances of parenchymal damage in decompression. The value of routine and special x-ray examination of subjects and other selection procedures has been analyzed (99).

Treatment of pneumothorax, pneumomediastinum, lung contusion, and aeroemboli resulting from explosive decompression has been recently covered (26, 99). The latest U.S. Navy tables for recompression therapy are recommended (19, 116, 123, 124). The objective of the recompression method is to expose bubbles to the optimum pressure gradient for efficient and rapid resolution while still permitting maximum oxygenation of tissues with circulation impaired with bubbles. Oxygen here has the effect of preserving function in ischemic vital areas and also interrupting the insidious cycle of ischemia, hypoxia, edema, obstruction, and further ischemia. An important collateral benefit is the absence of further inert gas saturation of the patient under recompression with pure oxygen. The volume of any spherical bubble decreases inversely with applied pressure. For chamber therapy, the treatment tables stop recompression at 165 feet gauge pressure because relative decrements of volume with increasing pressure become insignificant past 1/6 of the original bubble volume, while increasing the depth past 6 atmospheres (absolute) enormously increases the difficulties of subsequent decompression back to normal pressure, especially for an injured patient. The geometry of the situation dictates that the radius of the bubble decrease as the cube root of the applied pressure. The diminution of the radius, therefore, begins to become inefficient at shallower depths than 165 feet.

Bubble resolution in decompression sickness depends both on a reduction in size with recompression and on the elimination of inert gas from the bubble and from the surrounding tissue. In severely injured patients treated with recompression to 165 feet, inert gas exchange is grossly impaired in areas distal to obstruction. Bubbles may form during subsequent decompression in areas of tissue injury which have inadequate inert gas elimination rates due to circulatory impairment. The avoidance of further inert gas uptake by compressing only to 60 feet and the acceleration of inert gas elimination by oxygen breathing may overbalance any small decrease in bubble radius from further compression to 6 atmospheres. In patients for whom treatment has

been delayed and in whom vascular obstruction from edema and thrombosis may be of an importance equal to or greater than that from persistent bubbles, the hyperbaric oxygenation given immediately in treatment is believed to be of substantially more benefit than increased bubble compression with compressed air breathing.

The rate of recompression is another factor to be considered. The chambers at the NASA, MSC, Houston, can reach 7 psia within 25 seconds from onset of decompression (26). This time is certainly adequate for handling the emergencies outlined above. Ideally, the repressurization gas should be oxygen. However, the engineering problems and hazards involved in rapid recompression of a huge chamber with oxygen make this approach unfeasible (91, 101). Very rapid recompression can also be hazardous. Compression of animals over 0.5 atmospheres pressure difference in periods less than several milliseconds can lead to the same type of lung injury as seen in explosive decompression (71, 74). Restricting any emergency repressurization from vacuum through 7 psia to periods longer than 5 seconds should avoid permanent damage to the eardrums in most individuals (4, 56, 110, 111). In case of explosive decompression of space suits during EVA, the space cabin and suits should be raised to their highest design pressures (26). In most cases, this total will not exceed about 10 psia.

Treatment of the accompanying ebullism is covered below.

Ebullism

Exposure to altitude where the total ambient pressure approaches 47 mm Hg, the effective vapor pressure of fluids at body temperature, gives rise to the profuse evaporation associated with formation of vapor bubbles in tissues, blood vessels, and body cavities (102, 118, 122). Selection of vapor site is determined by such local factors as temperature, hydrostatic pressure, tissue elasticity, solute concentration (Clausius-Clapeyron factors) and presence of gas nuclei. As would be expected from these considerations, the large venous channels at the center of the body temperature core are sites of early bubble formation resulting in vapor lock of the heart. Subsequently, vapor pockets forming in the loose subcutaneous tissue are often seen, as are vapor bubbles in the aqueous humor of the eye and in the brain. In looking at the ebullism syndrome, one must also keep in mind damage to the body from hypoxia and lung pathology from explosive decompression (99).

There have been no exposures of the total unprotected human body to pressures in the ebullism range of significant duration. Exposure of only the hand to pressures of 5 to 30 mm Hg results in marked swelling with latencies which range from 0.5 to 10 minutes (122). The reason for such a range is not clear and may be peculiar to the experimental condition. The wrist and fingers can be flexed and extended through about 50 % of the normal range of motion. There is no pain associated with the swelling but only paresthesias in the area. Sudden recompression results in the swelling resolving at a pressure of 87 to 141 mm Hg in less than 0.5 minutes. Disruption of gloves in pressurized suits would probably lead to this condition.

The survival time of man exposed to near-vacuum conditions without pressure suit protection must be extrapolated from recent animal data. Early studies of explosive decompression of animals to very low pressures focused on the pathology to the lungs (7, 47, 58, 59). Even in the absence of pneumothorax, atelectasis appeared more severe than after explosive decompression to lower altitudes, probably because of vapothorax. Another key factor is suggested by the finding that only those animals in which respiration had ceased before recompression showed complete atelectasis. It is conceivable that water vapor entering the alveoli displaces the gas content and then recondenses on recompression to cause severe alveolar collapse. Otherwise the lesions were not much different from those of explosive decompression to lower altitudes.

More recent studies of ebullism cover the survival and functional capabilities of animals exposed to altitudes above 100,000 ft (8 mm Hg) (5, 7, 32, 43, 63, 69, 70). Decompression up to 130,000 ft (2 mm Hg) result in violent evolution of water vapor with swelling of the whole body of dogs. Preliminary results indicate that dogs kept as long as 90 seconds at 2 mm Hg did not present a single fatality. The animals were unconscious, gasping, and had bradycardias down to 10 beats per minute from the normal rate of 159 beats per minute, possibly a vagal response due to distortion of the mediastinal structures resulting from sudden expansion of the thorax. Most also had paralysis of hind limbs, yet after 10 to 15 minutes at sea level, they walked about normally. Animals exposed beyond 120 seconds did die frequently. Autopsy of surviving animals exposed less than 120 seconds demonstrate damage to the lung in the form of congestion, petechial hemorrhage, and emphysematous changes, the damage increasing with duration of exposure. Petechial hemorrhages and emphysema were more severe when decompression to altitude occurred within 0.2 seconds than when a decompression time of 1 second was used (43). Denitrogenation appears to reduce the incidence and severity of lung damage, possibly by reducing the inert gas entering the vapor bubble in the right heart (102). For the exposures of more than 120 seconds, gross examinations of the brain and other organs showed increasing amounts of congestion and hemorrhage with time at altitude. Occasionally dogs will die of cardiac arrhythmias possibly triggered by aeroemboli to the coronary arteries (see below).

Exposure of squirrel monkeys resulted in similar findings (104). Many of the survivors of 90 seconds exposure showed various defects in locomotion, hearing, vision, and food retrieval, and lost more weight than the control groups. Of interest, however, is the fact that among the survivors there was no loss of proficiency in learning set (69, 70). Chimpanzees can survive without apparent central nervous system damage (as measured by complex task performance) the effects of decompression to a near vacuum for up to 2.5 minutes and return within approximately 4 hours to baseline levels of functioning. One chimpanzee with intra-cerebral electrodes was at 2 mm Hg for 3 minutes. His time of useful consciousness was 11 seconds. Cortical silence started at 45 seconds; and subcortical, at 75 seconds. Two months later he still showed mild organic residua with performance and behavioral changes. It is of interest that in one case of death in these chimpanzees, no indication of disruption of the alveoli, alveolar ducts or bronchi was noted

on postmortem. Death was attributed to failure in the conducting mechanism of the heart.

For planning emergency procedures following decompression of protected humans to vacuum or near-vacuum conditions, a maximum survival time of 90 seconds should be used. Times of useful consciousness of about 10 seconds can be anticipated.

From the animal studies it can be inferred that upon prolonged exposure, cardiovascular collapse will be most precipitous and a major cause of death. After exposure to sub-ebullism altitudes, there is a dramatic fall in blood pressure followed by rebound with subsequent anoxic failure. Almost immediately after decompression to an ambient atmospheric pressure at which ebullism can occur, vapor bubbles form at the entrance of the great veins into the heart, then rapidly progress in a retrograde fashion through the venous system to the capillary level. Venous return is blocked by this "vascular vapor lock." This leads to a precipitous fall in cardiac output, a simultaneous reduction of the systemic arterial pressure, and the development of vapor bubbles in the arterial system and in the heart itself, including the coronary arteries. Systemic arterial and venous pressures then approach equilibrium in dogs at 70 mm Hg (96). At ebullism altitudes, one can expect vapor lock of the heart to result in complete cardiac standstill after 10-15 seconds, with increasing lethality for exposures lasting over 90 seconds. Vapor pockets have been seen in the heart of animals as soon as 1 second after decompression to 3 mm Hg (63). Upon recompression, the water vapor returns immediately to liquid form but the gas components remain in the bubble form. When circulation is resumed, these bubbles are ejected as emboli to the lungs and periphery. Cardiac arrhythmias often occur as do focal lesions in the nervous system (7, 27, 32, 33, 43, 69). These are probably a result of infarct by inert gas bubbles. The problem is aggravated by the concomitant generalized hypoxia. Cooling of the blood to 9°C by rapid evaporation in the alveoli while circulation is still intact, may delay the cardiac and cerebral response to ischemic hypoxia (4, 69, 96). The short cooling time precludes a more effective temperature drop.

Alteration of the gaseous environment may affect the ebullism syndrome. Data are available on the nature of the gas bubbles in the vascular system. Analyses of the changing gas compositions of subcutaneous vapor pockets by different investigators have given equivocal results (102). At first there appears to be a rapid conversion of liquid water to the vapor phase which reaches a peak at one minute and continues at a slower rate for several minutes. There is an initial rush of carbon dioxide, nitrogen, and oxygen into the pocket, but carbon dioxide and the nitrogen soon become predominant. If one can extrapolate to the more lethal vaporous bubbles in the great veins and right side of the heart, it would appear that the rate of growth and subsequent stability of bubbles after recompression would probably depend on the permeation coefficient or product of solubility and diffusivity ($\alpha_{\text{blood}} D_{\text{blood}}$) of the inert gas passing from the blood to the vapor bubble (102). Neon would enter the bubble more slowly than nitrogen, helium, or argon (order of increasing gas permeation). Once emboli have been ejected by the heart and have landed in the arterial system, however, the rate of resolution of the

bubble during therapeutic maneuvers will be inversely proportional to the ($\alpha_{\text{blood}} D_{\text{blood}}$) factor. Gas emboli containing only oxygen are safest, followed, in increasing order of hazard, by those of argon, helium, nitrogen, and neon. This would also hold for gas emboli entering the circulation from the injured lung.

It should be remembered, however, that presence of 100% oxygen in the space suit does not eliminate the problem of aeroemboli. Comparative effects of O₂, CO₂, N₂, and He emboli have been studied (38). Different volumes of these gases were injected into the internal carotid arteries of dogs prepared surgically so that the gas went only into the cerebral circulation without shunting to the extracranial arteries. Oxygen was tolerated without mortality but all the dogs had clinical or anatomic evidence of cerebral infarction. Carbon dioxide was well tolerated in doses up to 1.5 ml., but morbidity and mortality occurred with 2 ml. Nitrogen and helium foam produced effects similar to those of air foam, and morbidity and mortality results were comparable to the results obtained with air embolization. The physical basis for this difference is determined by the comparative resolution rates, and ultimately, by the permeation coefficients of different gas bubbles (72, 102). Occlusion of the circulation probably prevents the unsaturation of hemoglobin and reduces the size of the potential oxygen sink in the immediate surround of the intraarterial bubble. One must therefore anticipate that oxygen emboli will be somewhat less dangerous but cannot be neglected. For equal amounts of helium and nitrogen in the cerebral circulation, the hazard is probably equal. Empirical data are needed on gas effects on aero embism and ebullism.

Treatment of ebullism and related syndromes has received little formal attention. From the review of the pathological physiology of ebullism, it is apparent that in the treatment of this syndrome in space operations or in chambers one must consider damage to the lungs from exposure to cold (96), from hypoxia, and from gas embolization arising in the large veins and right side of the heart. One must also consider arterial gas embolization through atrial septal defects or vascular shunts in the lung. Fortunately, therapy of contusive damage to the lung covers damage to the lung from ebullism (99). In chambers on Earth, the Trendelenberg position may decrease the embolization of the lungs (99). Aspiration of gas from the right ventricle in the case of cardiac arrest may aid in restoration of the circulation and avoid further damage to the lung by gas emboli. Treatment of arterial or venous gas emboli after ebullism should be no different than that following lung disruption. Compression therapy suggested for the latter should have no deleterious effects on the former. As in contusive damage, progressive pulmonary edema and atelectasis must be anticipated after prolonged exposure of the lung to vacuum. In view of the atelectatic tendency, prolonged treatment with 100% oxygen should be used only when cyanosis and oxygen unsaturation of the blood are present in cases uncomplicated by obvious embolization (100).

Exposure to hypoxic environments for longer than 3 or 4 minutes may produce several of the post-hypoxic syndromes during the treatment period. These have recently been reviewed in great detail (26). It may be difficult to distinguish post-hypoxic cerebral edema from brain syndromes associated with massive air embolization. Failure of a patient to respond to recom-

pression therapy (persistent coma or delirium) should raise the consideration of post-hypoxic-cerebral edema. Dehydration therapy would then be in order. It is suggested that mannitol be given intravenously in concentrations up to 20% with doses up to 200 Gm per 24 hr period (26, 75). Hypothermia may also be used for the post-hypoxic syndrome to minimize damage to the brain elements and break up the vicious edema-hypoxia cycle (26). It has been recommended that body temperatures between 30°C (86°F) and 32°C (89.6°F) be attained with suppression of shivering by chlorpromazine (52.125). The value of steroid-antihistamine combinations for post-hypoxic cerebral edema is yet to be determined (104).

The bizarre electrocardiographic patterns seen in dogs exposed to vacuum range from extrasystoles to idioventricular rhythms and ventricular fibrillation (25, 31, 96). Cardiac dilatation (from trapped gas), hypoxia, vaporization of intracellular water, exposure to cold blood, and air emboli may all probably play a role. Electrical defibrillation and not just anti-fibrillatory drugs should be used to reverse the ventricular fibrillation and tachycardia (49). Lidocaine is effective if P. V. C. 's or ventricular tachycardia occur after electrical defibrillation. The dose of lidocaine is 1-2 mg/kilogram body weight given intravenously in 1-2 minutes, repeated if necessary once or twice at 20 minute intervals. For idioventricular rhythm with rates greater than 150 per minute, as ventricular tachycardia, the treatment should be lidocaine. Idioventricular rhythm with a rate of less than 100 per minute implies that ventricular escape has occurred and treatment with lidocaine is contraindicated. On Earth, a transvenous pacemaker should be used. This maneuver, by increasing the ventricular rate, will usually suppress the ectopic focus, but if the attempt is not successful, cardioplegic drugs may then be used with a greater measure of assurance. Idioventricular rhythms with rates between 100 and 150 per minute present a difficult problem. One can try treatment with lidocaine but if dysfunction of the conduction system appears to be present, an artificial pacemaker should be used (93).

Blast Overpressure

The hazard of blast overpressures from meteoroid penetration or explosions within a spacecraft results from direct blast damage to the ears and lungs and secondary damage to the body from non-penetrating missiles, penetrating missiles, and sudden impact against large structures (101, 121). The time-geometry of the effective blast wave is critical in determining levels of injury expected from any overpressure. Such factors as the incident wave form (rise time, peak pressure, duration, and pulse tail-off), dynamic pressures, reflected waves and their timing, ambient pressures, positioning of subject relative to blast direction, geometry of surroundings, etc., all are critical (97, 121). The term " effective pressure " will be used to cover the overpressure equivalence of all these conditions. For space operations, the ambient pressure is most important in biological scaling (22, 35, 36). For lethality, lung damage, and possibly eardrum damage, the overpressure in psia for 50% effect (P_{50}) at any ambient pressure, (X) relative to sea level (SL) is:

$$P_{50}(x) = P_{50}(SL) \left(\frac{x}{14.7} \right) \quad (17)$$

The scaling equation in Figure 12-21d includes this pressure factor.

Lethality

Blast overpressures produce their lethal effect by primarily disrupting the alveolar and vascular structures of lungs causing hemorrhage and respiratory embarrassment (101, 120). Gas emboli entering the circulation from disrupted pulmonary veins can pass to coronary or cerebral circulation and cause death by infarction of the tissues. The maximum tolerable overpressure is a function of the pulse duration and geometry of exposure, including such factors as body position relative to the blast wave and to reflecting structures.

The threshold, 50% and 100% lethality levels for short and long duration blast are seen in Table 12-20. For atypical or disturbed wave forms of "long duration," tolerance can be estimated to increase by about a factor of two for pressures rising to a maximum in two "fast" steps and by a factor of 3 to 5 for wave forms rising smoothly to a maximum in 30 or more msec.

Figure 12-21a to c are preliminary estimates of human survival after air blast exposures of different duration and geometry of incidence. Figure 12-21d presents scaling criteria and animal data from which human thresholds were derived. These figures show some of the geometric factors which must be considered in evaluating the blast hazards resulting from explosions of boosters on launch pads or of space cabins in orbit.

Lung

From animal studies it appears that death, if it does occur, will overtake more than 90% of the animals within the first 30 minutes after exposure (120). This can probably be applied to man as well. Threshold overpressures for lung damage and probably secondary emboli are seen in Table 12-20. Figures 12-21a to c give the threshold overpressures for lung damage under different geometries of incidence and duration of exposure.

Damage to the lungs by overpressures resulting from meteoroid penetration of spacecraft has been reviewed (102). Overpressures of less than 1 msec with rise times as short as 15 microseconds may be anticipated. Effects of these overpressures are complicated by the flash-oxidation of molten metal resulting from penetration of the cabin wall by the meteoroids. Inhalation of hot metallic vapors may increase lung damage brought about by the blast overpressure. More quantitative work on this problem is needed.

Damage to the lung from excessively rapid recompression from a vacuum is covered on page 12-30.

Ear

Damage to the eardrum is also a significant factor in blast injury (113, 120, 121). The maximum overpressure is a major blast parameter to be considered, but the rise time and duration of pulse are also significant. The slower the rise time, the greater the peak overpressure needed to disrupt the drum. The longer the duration of overpressure, the greater the percent of disruption at the same peak overpressure (120). Tentative estimates for short- and long-duration effects in man are shown in Table 12-20. The exact scaling of ambient pressure and wave-form effects for man are less certain for eardrum rupture than for lethality.

Figure 12-22 represents an estimate of population response to peak overpressure with drum disruption as an endpoint.

Figure 12-20

Tentative Criteria for Primary-Blast Effects in Man Applicable to "Fast"-Rising Air Blasts of "Short"-Duration (3 msec) and "Long"-Duration (Plateau > 20 msec)*

Critical Organ or Event	Maximal Effective Pressure (psia at sea level)*	
	<u>Short</u>	<u>Long</u>
<u>Eardrum Rupture</u>		
Threshold	6	6
50 Per Cent	18	18-25
<u>Lung Damage</u>		
Threshold	37-49	12-14
Severe	100 and above	—
<u>Lethality</u>		
Threshold	120-140	37-52
50 Per Cent	160-220	51-70
Near 100 Per Cent	250-310	70-98

Effective pressure can be the incident, reflected, or incident plus dynamic, depending on one's geometry of exposure and the location of the explosion. The data on lung damage and lethality correspond to those of Figure 12-21; the data on eardrum rupture (short duration), to Figure 12-22.

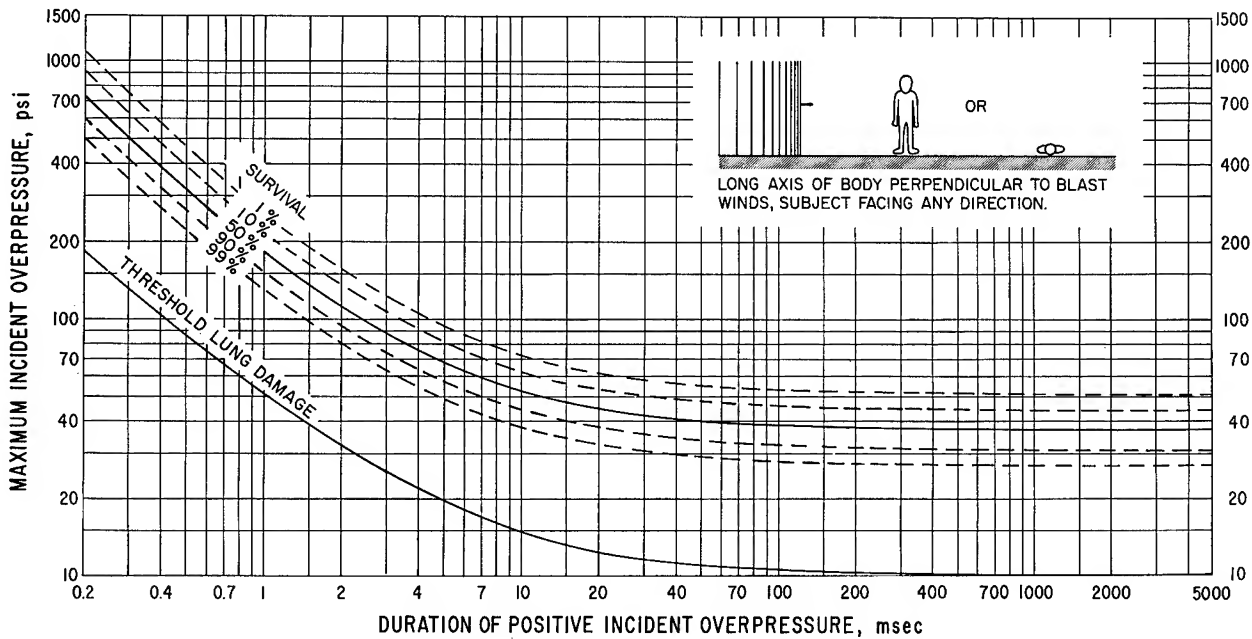
(After Richmond et al⁽⁹⁷⁾ and White⁽¹²¹⁾)

Figure 12-21

Estimate of Survival and Lung Damage Thresholds for Humans Exposed to Air Blast

(After Bowen et al⁽²¹⁾)

a. Long Axis of Body Perpendicular to Blast Winds, Subject Facing Any Direction



b. Thorax Near a Reflecting Surface Which Is Perpendicular to Blast Winds, Subject Facing Any Direction

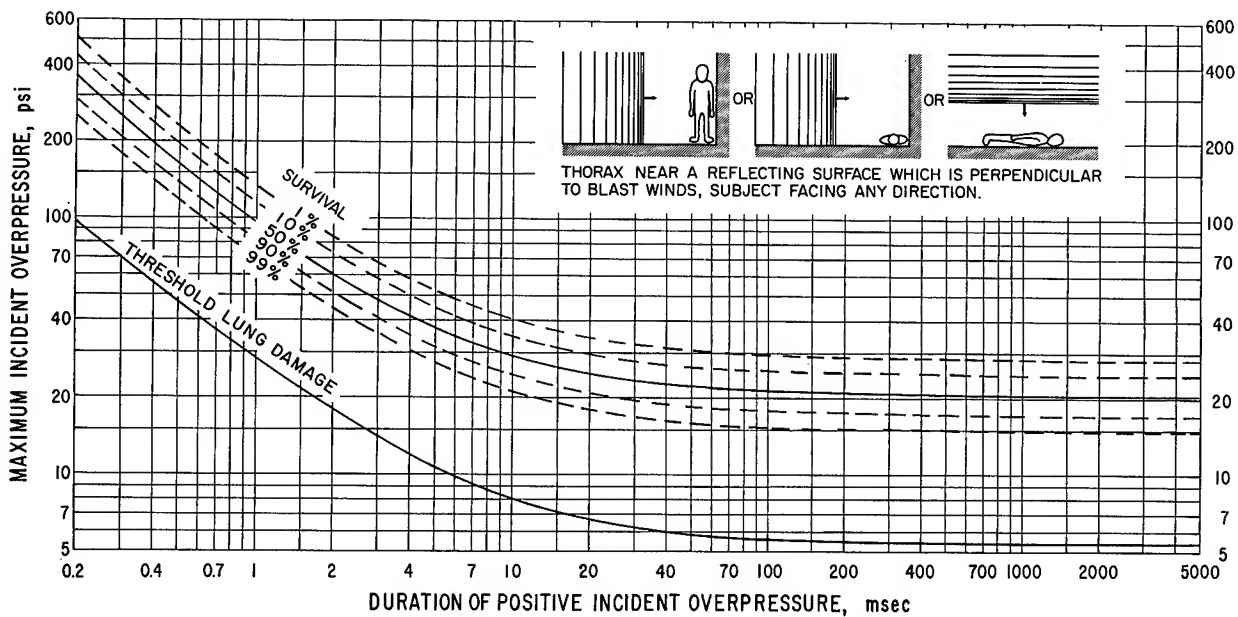
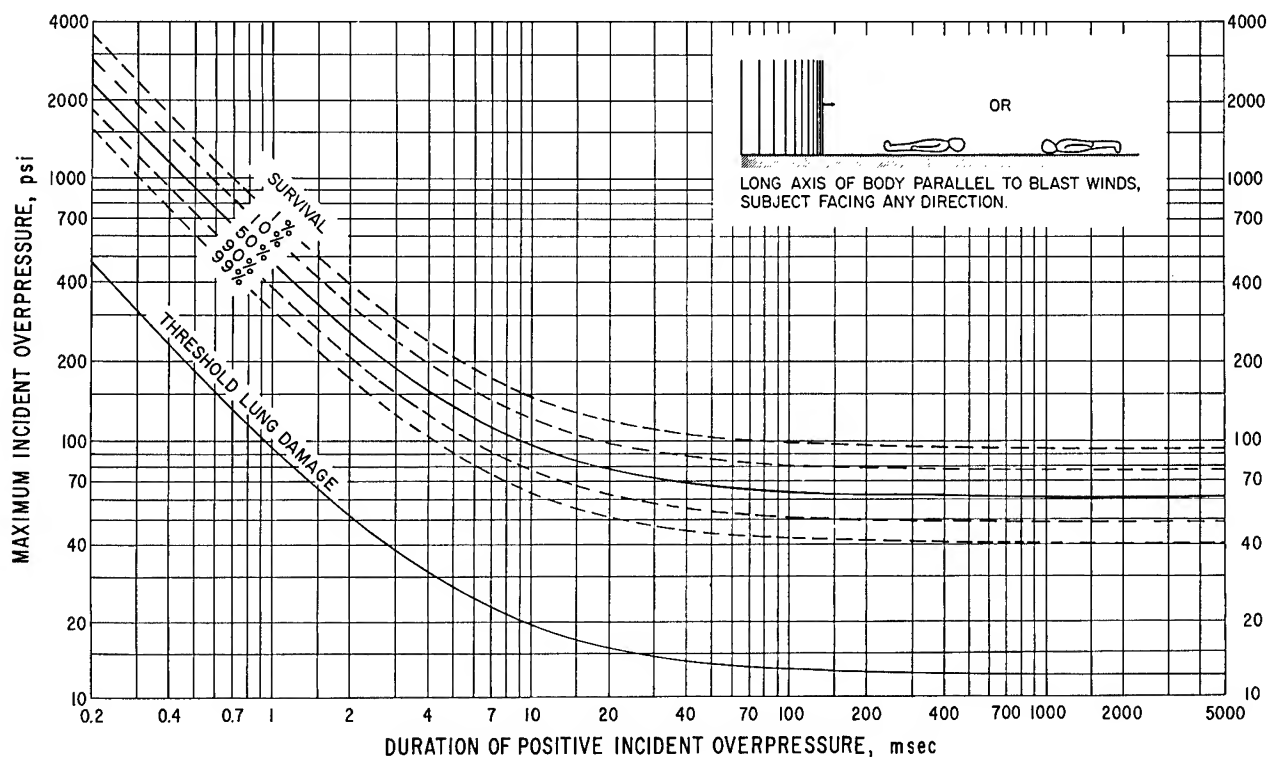
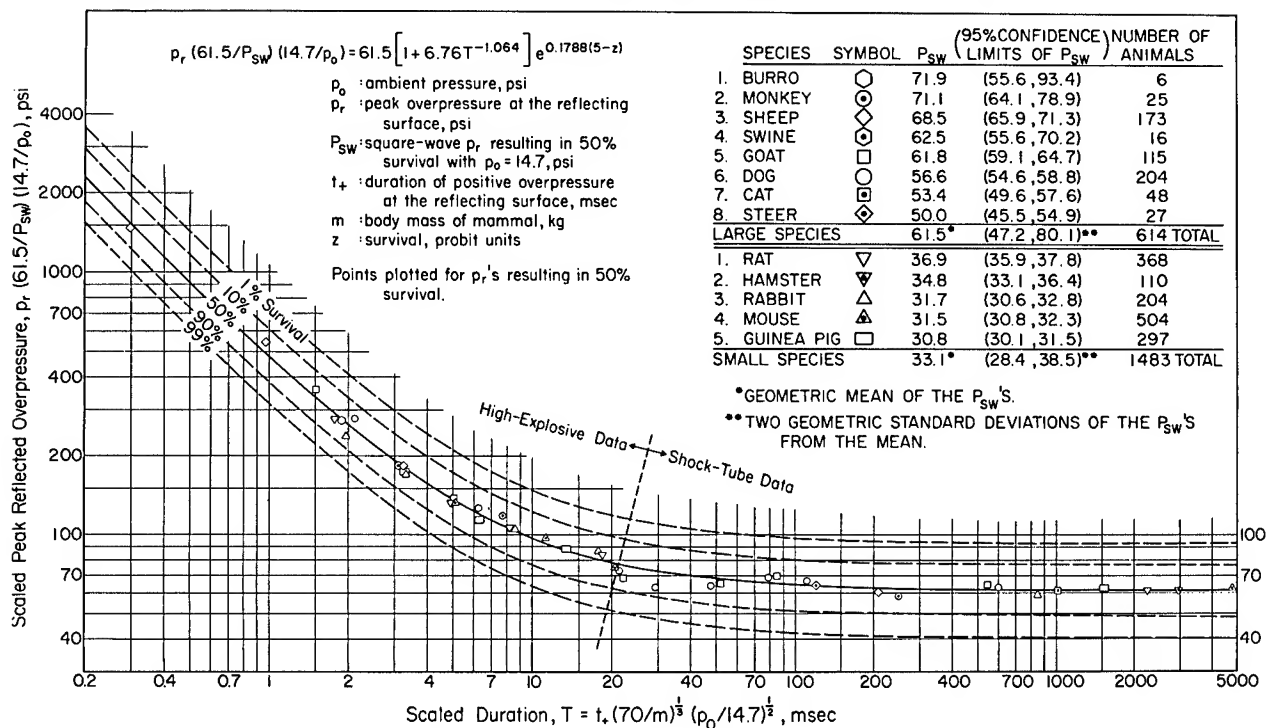


Figure 12-21 (continued)

c. Long Axis of Body Parallel to Blast Winds, Subject Facing Any Direction



d. Scaling Factors by Which Animal Data Have Been Extrapolated to Humans



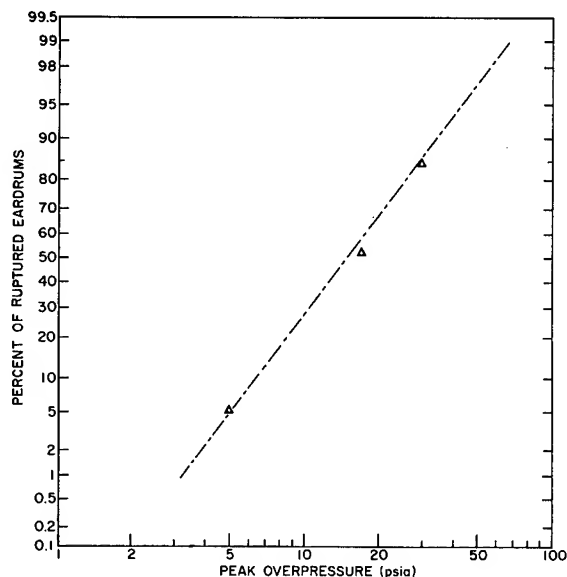


Figure 12-22

Tolerance of Eardrums to Fast-Rising Overpressures
Estimated from Combined Human Data (Δ)

(After Hirsch⁽⁵⁷⁾)

The most significant effect of blast injury to the ear is damage to the organ of Corti and resulting loss of hearing, both temporary and permanent. It is felt that when the eardrum is disrupted, injury to the inner ear is less and the deafness less grave and less permanent than when the same overpressure does not disrupt the drum (57). In the presence of drum rupture, the hearing loss is of mixed type with both low-frequency loss of middle ear damage and high-frequency loss of inner ear damage. (See Sound and Noise, No. 9). Usually the low-tone loss will be in the order of 10-30 dB and the high-tone loss of 40-80 dB. When dislocation of the ossicles accompany drum rupture, usually in "long-duration" blast, a permanent, severe, conductive loss is sustained. The size of the perforation does not correlate with hearing loss. Up to 78% of cases of temporary deafness can occur without perforation (18). There is an accumulative effect of multiple blast insults to the ear with progressive conversion to permanent hearing loss.

Because of the great variation with age and secondary factors, there is little correlation of dB loss at any frequency with the blast overpressure sustained at the ear level. Figure 12-23 represents a typical audiogram following a fast rise-short duration overpressure of 30 dB which disrupted both eardrums. After healing of the perforation the audiogram returns to normal except for residual high frequency loss. As is indicated, conversational tone reception may not be compromised. The effect of impulse noise is under study (60, 61).

Recompression damage to the ear is covered on page 12-30.

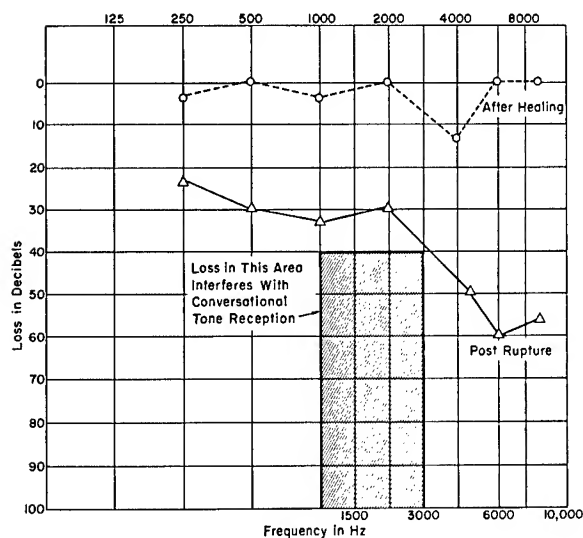


Figure 12-23

Typical Audiogram Following Short Rise Time-Short Duration Overpressure of 30 Psia with Drum Rupture

(After Hirsch⁽⁵⁷⁾)

Heart

Lowering of the blood pressure sometimes to the point of shock, slowing of the pulse and an increase in the respiratory rate have been frequently observed in experimental animals exposed to explosions. The shock-like state occurs too rapidly to be associated with loss of blood in the lung tissue, so explanations have been sought through reflex mechanisms. It thus appears that the tissue injury of the lung may induce reflexly through the vagus nerve a shock-like state with a slow heartbeat. The situation is later complicated by loss of blood into the lungs and reduced oxygen supply secondary to the reduced capacity of the lung for air. Heart failure secondary to failure of the circulation of blood to the heart muscle brought about by an emboli has also been noted and sometimes appears to be related to sudden death in experimental animals.

Abdominal Viscera

Hemorrhage into air-containing abdominal viscera, particularly the gastrointestinal tract, has been reported following both air and water blast. As for the lungs, the basic mechanism for injury would appear to be relative displacements among tissues at boundaries where the medium changes abruptly from fluid to gaseous. In air, injury to the lungs occurs more easily than injury to the abdominal viscera. Because of better shock-wave coupling, underwater explosions of mines near sailors swimming in water have been noted to produce more severe injuries to the air-filled abdominal viscera than to the lungs.

Brain

The mechanism of injury to the brain from shock waves in air remains somewhat obscure. Both large and small hemorrhages in the substance of the brain and in the tissues surrounding the brain have been observed in both man and experimental animals. Such injuries usually occur after exposure to extreme and nearly mutilating blast conditions. There is experimental

evidence that under less severe conditions some of these hemorrhages are secondary to interference with the circulation to the brain by bubbles of air in much the same way as described above for the heart (120).

Skeleton

Injuries to the bony skeleton from shock waves reaching man through air or water have not been reported. On the other hand, shock waves reaching man through solid supporting structures have produced severe fractures and dislocations of the skeleton. Transients applied to the base of the spine of a seated man can produce fractures and dislocations of the spine with paraplegia as a consequence. Although injuries to the lower extremities while standing and to the spine while seated are most common, other postures with varying degrees of contact with solid structures can produce other more bizarre injuries (120). (See Impact in Acceleration, No. 7.)

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13. CONTAMINANTS STANDARDS

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The evaluation of the contaminant hazard in space operations is a difficult problem that has as yet not been adequately solved. The variables and unknowns are numerous (94, 203). Data to be presented below will be restricted to those empirically derived. An attempt will be made to present those theoretical considerations which must be understood in order to extrapolate the data to space cabin conditions. In view of the current uncertainties regarding the data, no recommendations will be made on limits for continuous exposure to toxic trace contaminants other than those suggested by the NAS-NRC (136).

GENERAL EVALUATION OF THE CONTAMINANT PROBLEM

Toxicological problems in space operations cover three situations: (1) the acute, short term, high-level exposure either in ground support or space cabin conditions; (2) the 8-hour work day exposure found in manufacturing and ground support situations; and (3) continuous, long term exposure to trace contaminants, such as would be anticipated in extended space missions.

A completely new and unique aspect of toxicology has evolved from the aerospace mission, for which no parallel exists in previous experience in industrial hygiene or occupational medicine. This situation exists for two reasons: the increased use of multi-ton quantities of high energy, physiologically-reactive compounds with the inherent increased possibility of accidental exposure; and the contemplated long-term space mission within a closed system, in which, unlike submarine conditions, unlimited power is not available for complete control of the environmental atmosphere. The greatest need for toxicological information in both situations is for inhalation data. Up to the present, the only guidelines available to the toxicologist are the Threshold Limit Values (TLV) established by the American Conference on Governmental and Industrial Hygienists (6, 199), the maximal allowable concentrations of the American Standards Association's Z-37 Committee (210), and the more recent recommendations made by the ad hoc committee on Air Standards of the Committee on Life Sciences, National Academy of Sciences (136). These values represent, for the most part, time-weighted average concentrations to which nearly all workers can be exposed 8 hours daily, 5 days per week throughout their working lifetime without adverse effects on health. The last of these guidelines extends few TLV data to space conditions.

Safe exposure levels to air pollutants in community, industrial and military situations are based mainly on industrial experiences, animal studies, human volunteer exposures or a combination of the three. Because it is rare that industrial experience can supply both environmental and medical data adequately controlled in respect to exposure conditions, data from animal studies are more commonly used where such controls can be maintained and the progress of the response determined at will. Increasing use of data from human volunteer exposures is being made to provide the desired correlations

between animal and human experiences. Data from whatever source is then evaluated by a committee of individuals of long and continuing experience in industrial health for what limit in their judgment is appropriate. The continual surveillance on the suitability of the industrial air limits, which now number more than 400 and a substantial number (67%) of which have been satisfactorily used without change for from 20 to 25 years, offer mute testimony to their validity. In this connection, it is interesting to note that experience has been equally good with industrial air limits based on animal studies as those based on human experience and industrial surveys (65%). (198) Each limit is documented by pertinent literature references with a clear statement on the nature of the response against which the limit protects.

It should be most emphatically noted that in our present state of knowledge none of the industrial air limits can be used with certainty either directly or by extrapolation for space cabin environments. Although such an extrapolating equation has been proposed (200) in which all variables likely to affect toxicity were included, subsequent experimental animal work (205) showed that such a procedure could not be relied on in any given case; in our present state of knowledge, the rate of metabolism varied unpredictably from one pollutant to another under conditions of continuous exposure relative to intermittent exposure. This parameter appeared to be overriding, at least as far as animal studies indicated, but it should be noted that animal studies are incapable of revealing the magnitude of several of the factors included in the extrapolation equation. How unpredictable is the application of the TLVs of industry to space cabin conditions is shown in the above-mentioned studies (205). The intermittent, 8-hour industrial TLV for phenol appeared to be a satisfactory TLV for the 90-day continuous TLV for space; possibly also for carbon tetrachloride, but not for hydrazine, unsym. dimethyl hydrazine, nitrogen dioxide, decaborane, hydrogen sulfide or methyl mercaptan.

The industrial air limits would appear to be also inadequate for extrapolation to the space cabin environment in terms of other critical factors of the environment such as pressure, atmosphere, relative humidity, radiation, thermal, and other factors. Even the 90-day exposure limits set for submarines are not directly applicable because of these variables (27, 151, 200). Efforts to use these values when mixtures of toxic materials are involved, as is almost always the case in aerospace situations, are not only meaningless but dangerous.

In view of the necessity for provisional limits of manned space flights of 90- to 1000-days' duration, the NAS-NRC committee has derived the following criteria for trace contaminant control in manned spacecraft (136):

- 1) Contaminants must not produce significant adverse changes in the physiological, biochemical, or mental stability of the crew.
- 2) The spacecraft environment must not contribute to a performance decrement of the crew that will endanger mission objectives.
- 3) The spacecraft environment must not interfere with physical or biological experiments nor with medical monitoring.

For the purposes of these provisional criteria, the Committee assumes a spacecraft atmosphere ranging from 760 to 258 mm Hg total pressure, containing nitrogen as a diluent gas, oxygen sufficient to maintain normal (sea-level equivalent) alveolar partial pressure, and carbon dioxide below 5 mm Hg. Temperature and relative humidity are within the comfort zone for the total pressure selected.

This rigorous approach is also consistent with scientific requirements. The NASA Space Medicine Advisory Group and the Respiratory Physiology Group of the Space Science Board's 1966 Summer Study have reaffirmed the principle that engineering exigencies should not dictate the environment: the environment must be supplied to provide the best medium for the experimental effort and one might also add, the best medium for the mission profile. Thus, if one of the goals of prolonged manned spaceflight is to ascertain man's adaptability and response to the weightless environment, it is necessary to design manned spacecraft in such a fashion that the Earth atmosphere or a reasonable facsimile thereof be provided in order not to prejudice the study of the one facet of spaceflight that cannot be duplicated on Earth - weightlessness.

The NAS-NRC has therefore developed conservative air quality standards for prolonged manned missions on the following premises: (136)

- 1) Any contamination of the spacecraft atmosphere may be detrimental.
- 2) Zero contamination level of the spacecraft atmosphere is impossible.
- 3) Data do not exist that will permit one to predict with certainty the maximum contaminant concentration that will not cause degradation of the mission.
- 4) Provisional limit values can be established for some contaminants to serve as guidelines in design, development, and testing of future space systems.
- 5) These provisional limit values can, perhaps, ultimately be transformed into limit values if sufficient data about the effects of continuous exposure to a single compound and to multiple compounds can be obtained.

The uncertainties in establishing even provisional limits for prolonged manned missions are many and range from engineering, to environmental, to toxicological considerations. Since the materials to be used in future spacecraft construction and the type of regenerative environmental control system(s) to be employed have not been determined, there are major uncertainties regarding the kind and amount of air contaminants that will be present. There is also a major uncertainty as to how reduced pressure may alter the toxicity of contaminants.

A further consideration is the fact that most of the available data have been obtained on subjects in a "normal" physiological state. The effect of stress, prolonged confinement, weightlessness, and other factors that might

tend to alter man's normal physiology, and thus change his response to any given compound cannot be accurately predicted at this time. For all these reasons, the limits recommended by the NAS-NRC Committee are provisional, and subject to revision. (See discussion of Table 13-15 on page 13-56.)

Programs have been established to provide specific toxicological information on selected propellants and to study the effects of long term, continuous exposure to possible trace contaminants at reduced atmospheric pressures and under the influence of one- and two-gas systems (oxygen or oxygen/nitrogen) (2, 136, 203). These programs include definitive measurements of physiological changes as evidenced by clinical chemistry, changes in behavioral patterns, and gross and microscopic pathology. It is hoped these will allow a more definitive evaluation of the space cabin problem.

KINETICS OF CONTAMINANTS IN SPACE CABINS

Units

There are several ways of expressing exposure or dose. One procedure describes the quantity in terms of a weight or volume of material per unit weight of the animal, for example, mg/kg. When speaking of the concentrations of a gas or particulate in the air, the term parts per million (ppm) or mg/cu M are generally employed. The former is a v/v relationship. In air exposures the time of contact in minutes or hours is included. In the space cabin environment with an altered partial pressure of the atmosphere, it has been suggested that micromoles/cu M or millimoles/25M³ may be a more reasonable way to express the data (136). The latter unit gives a numerical value which, at 1 atmosphere pressure and at 25°C, is the equivalent of ppm by volume (the units used for submarine standards and by the American Conference of Government Industrial Hygienists). At the same time it expresses the molar concentration per unit of space volume and is, therefore, equivalent to partial pressure of the contaminant. Unfortunately, the toxicological literature makes little or no use of these expressions as standard terms.

The percent of animals affected is defined as a subscript 0, 50, or 100, etc. Since lethality is often the outcome, a lethal dose is abbreviated as LD and the lethal concentration as LC. When subscripts are not used, the value has probably been based on limited observations and hence lack statistical validity. The concept of threshold limit value (TLV) and maximum allowable concentration (MAC) has been discussed above.

Buildup of Contaminants

The primary and secondary factors controlling the buildup of contaminants in sealed cabins are seen in Table 13-1. Asterisks indicate those factors not present or significantly different in submarines.

Table 13-1
Important Factors Influencing Atmospheric Contaminations in Sealed Cabins
(After Thomas (203))

<u>Aggravating</u>	<u>Beneficial</u>
Continuous Generation and Exposure	Leak Rate of Cabin
* Reduced Pressure	Materials Selection
* Volume/Man Ratio	Preconditioning of
* Power and Weight Limitation	Materials
Filter Characteristics	
Complexity of Contaminants	
* Multi-Stress of Environment	
* Escape Lead Time	

* Not significant in nuclear submarines.

For a given compound or element, the concentration of its vapors within a closed space is determined by the difference in the rate at which the vapor is generated, and the rate at which the vapor is removed from the atmosphere of the closed space:

$$\frac{d}{dt} C = \frac{d}{dt} G - \frac{d}{dt} A, \quad (1)$$

where C = rate of contaminant buildup;

G = rate of contaminant evolved;

A = rate of contaminant removed.

G is a function of the Molecular Weight of the compound or element, of the surface area exposed to the specific cabin atmosphere, and of its temperature in usage. These parameters determine the "contaminating efficiency." A is the "decontaminating efficiency" of the Environmental Control System, and is usually designed on principles of chemical removal, or of physical removal, or of a combination of both (ex: chemisorption, or reaction; cryogenic condensation, or physical adsorption). By these means, the contaminant is brought into a solid or liquid phase having a considerably lower vapor pressure than the original.

The surface area of the material exposed to the cabin atmosphere must be known, or closely estimated. The vapor pressure of the contaminating material and its usage temperature, as well as its molecular weight must be known, or calculated from Equation (2):

$$\text{Log}_{10} p = - \frac{0.0523}{T} A + E, \quad (2)$$

where p = pressure in mm Hg of the saturated vapor
pressure at temperature T;

T = temperature of material, degrees K;

A, E = constants, the values of which are reported in the literature for a vast number of chemical elements and compounds (51, 88, 93, 129, 157, 193).

The weight rate at which contaminating vapor is generated as a function of its molecular weight and temperature must be known, or calculated by the Langmuir equation:

$$G = \frac{p}{17.4} \cdot \left(\frac{T}{M}\right)^{\frac{1}{2}} \quad (3)$$

where G = weight rate of vapor generated, in gms, per unit area of contaminating material;

p = pressure in mm Hg of the saturated vapor pressure at temperature T ;

T = temperature of material, degrees K;

M = molecular (atomic) weight of material.

For toxicity evaluation purposes, the above information is useful when rendered in units of parts per million by volume. Therefore, the free volume, V_f , of the closed cabin must be known, or closely estimated, and the cabin pressure, P_c , must also be known. Hence, integration of Equation (1) over the time considered yields the mass (in grams) of contaminant in the closed cabin atmosphere, per unit area of material.

Equation (3) may be more useful and more easily handled, as the weight of contaminant is determined directly by multiplying the value of G by the time and the surface area (time interval over which the calculation is made, e.g., mission time; and surface area of material exposed to cabin atmosphere):

$$G \text{ in } \frac{\text{gms}}{\text{Cm}^2 \cdot \text{Sec}} \cdot \text{Cm}^2 \cdot \text{Sec} = G' \text{gms} \quad (4)$$

Then:

$$V_a = \frac{G'}{M} (22,415) \quad (5)$$

where V_a = volume of the G' weight of contaminant, atmospheric pressure, cubic centimeters;

M = molecular (atomic) weight of contaminant grams;

22,415 = volume of 1 mole contaminant at 760 mm Hg pressure, in cubic centimeters;

And then, correcting for cabin pressure,

$$V_c = V_a \cdot \frac{760}{P_c} \quad (6)$$

where V_c = volume of the G' weight of contaminant, at cabin pressure, cubic centimeters;

P_c = pressure of cabin atmosphere, mm Hg.

This volume, V_c , may now be expressed in parts per million of free cabin atmosphere:

$$\text{ppm} = \frac{V_c}{V_f} \cdot \frac{F}{F} \quad (7)$$

where V_c = volume, in cm cubic, as defined above;

V_f = free volume of closed cabin, in cc.;

F = of a value such that when multiplied by V_f yields a product of 1 million.

Ideally, the above considerations could provide the basis for controlling the undesirable constituents of space cabin atmospheres providing that in each case an appropriate exposure value could be stated. Were it possible to do this and if the expressions above could be organized into a set of nomograms, a desirable way to present the information would be to develop a final nomogram combining Equations (5), (6), and (7) with a scale of limiting values for concentration and duration of exposure. Sets of such nomograms might be developed each for a different class of contaminant. This ideal cannot yet be achieved.

The concentration of a contaminant in a cabin at time t after closure can be determined by the equation:

$$C = \frac{W}{b} (1 - e^{-\frac{bt}{a}}) \quad (8)$$

where C = mg/m³ of contaminant at time t ;

W = mg contaminant generated per day;

a = m³ total effective gaseous volume;

b = m³ atmosphere leaked per day at x psia;

t = days elapsed time;

e = 2.718.

This equation suggests that an equilibrium level of contaminant will be reached. The time to reach 99% of equilibrium concentration after closure can be estimated by the equation:

$$t_{\text{days}} = 4.6 \frac{a}{b} \quad (9)$$

where a = m³ total effective volume

b = m³ leak per day at x psia.

The concentration at equilibrium and the time to reach this concentration (Equation 9) are determined by the variables of Equation (8). This is a key factor in establishing the relative rate of chemical removal and purge or venting removal needed to attain a given equilibrium level in the atmosphere.

To summarize the salient features of the contaminant build-up hazards, the following axioms can be stated: (204)

- Given a certain cabin volume, the time of equilibration of contaminant concentrations in the atmosphere is independent of the final concentration attained, if contaminant generation and removal rates are held constant. Under certain conditions, the virtual (but not the true) rates of contaminant generation can become constant since the decreasing rate of gas-off from materials is balanced out by the progressive loss of filtering efficiency.
- The magnitude of the final equilibrium concentration of contaminants is directly proportional to the generation rate and inversely proportional to the removal rate in sealed cabins.
- Contaminant concentration rises rapidly at first and then approaches a constant value (equilibrium concentration) at infinite time.

From a practical standpoint, the design engineer has primarily to worry about contaminant removal rates to keep the atmosphere habitable on long duration missions. Removal rates depend on what contaminants are lost together with the cabin atmosphere as the result of outboard leak and the amount of contaminants that are adsorbed on the various filter beds. Leak rates are the most effective disposal methods for contaminants. They also have the greatest impact on the rate at which contaminants accumulate in the cabin (230). Since large leak rates are undesirable from a logistics standpoint, other means of contaminant elimination must be found. To simplify calculations, "equivalent leak-rate times" can be used for rating filters, scrubbers or other air purification equipment. This "equivalent leak-rate time" (ELRT) can be defined as the volume of atmosphere that has been "absolutely cleaned of contaminants" in one day's time, with specific consideration for the efficiency of the purification unit. For example: A filter operating at 50% efficiency would remove only 1/2 of the contaminants present in a unit-volume of air passing through it. On the second passage through, it would remove 1/2 of the remainder, etc.

In evaluating the buildup rate, important secondary factors to be considered for each contaminant are the kinetics of adsorption along adsorption beds and the break-through curves for the gas-bed system (33, 157). The problem with filters is that their efficiency decreases with time as the filter bed saturates with contaminants and as the flow rates through the filter drop due to particles obliterating the free passage of atmosphere. Typical curves are seen in Figure 13-2. These curves also determine the nature and timing of secondary chemical reactions which can occur on the bed and thus the alteration in the nature of the trace contaminants to be considered. It can be seen that with increasing time, filter efficiency decreases in an exponential fashion that is quite similar to the build-up of contaminants. Consequently, the inefficiencies of filters on long-duration missions will be greatly aggravated by the contaminant build-up if there is no substantial outboard leak or controlled dumping. Moreover, nuclear submarine experience indicates that adsorbent beds become saturated with high boiling hydrocarbons within two to three days and permit the low boiling point materials to pass through,

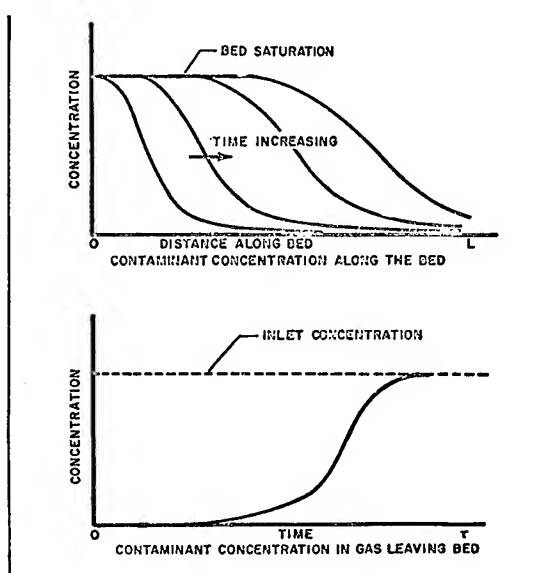


Figure 13-2
Concentration Profiles in Sorption Beds
(After Thomas (203))

even displacing these. Until specific adsorption coefficients become available for particular materials and periods of time, generous safety factors should be used in calculating the amount of adsorbents. Preliminary design data are available on isotope-heated, catalytic oxidizing systems for contaminant removal in future space vehicles (142).

Generation of contaminants can be controlled by appropriate care in the design and manufacture of space cabins. A handbook is available covering recommendations for contaminant control in the Apollo Program (138). The Soviet approach to the kinetics of contaminant control has been recorded (24).

TOXICOLOGICAL FACTORS

All compounds capable of chemical reaction have an adverse effect on the body at some quantity or concentration (50, 52, 145, 177, 218). Toxicity is inherent in all substances; the question, therefore, is: what is the intensity and duration of the exposure? By the process of homeostasis through alteration of physiological and biochemical mechanisms, the body is capable of maintaining its normal healthy internal environment up to a point. If that point is exceeded, then adverse effects may occur. Exposure to chemical substances may be single, repeated, or continuous. The vast majority of toxicologic research has been based on the first two of these relationships. As a rule, a single exposure, if it does not result in death, does not produce persistent deleterious effects in biochemistry, physiology, or structure; but this may not be so in the case of carcinogens. Recovery occurs rapidly. However, in the case of substances taken into the body repeatedly or continuously, while not producing immediate change, may slowly exert a deleterious effect. This occurs in one of two ways. Either the substance may collect in the body to such an extent that eventually the concentration is great enough to cause change; or repeated small injuries may summate to the point where normal biochemical, physiological, or tissue-restorative abilities are exhausted. Agents like carcinogens or beryllium may have complex dose-intermediate-response relationships.

Classification of Toxic Agents

Toxicological agents may be classified in many ways. The following is one of the simplest breakdowns relative to the space problem.

- 1) Asphyxiant. Any agent which interferes with the oxygen supply or its utilization. In the narrower definition of this term, the presence of increased carbon dioxide in blood or tissues is added.

- a) Simple asphyxiant. These act by physical displacement of the oxygen available in the atmosphere and, thereby, reduce the concentration of oxygen in the lungs. This type of agent is effective only at relatively high concentrations and, therefore, can be detected easily. For this reason, it is not likely to be important as a trace contaminant.

- b) Biochemical asphyxiants. These act by blocking any step along the path of oxygen transport or utilization. Since most of these agents are very active biochemically, they may be effective in very small concentrations. Any agent blocking the respiratory center will cause hypoxia and CO₂ retention. As another example, carbon monoxide has a much greater ability to bind hemoglobin than does oxygen. Thus, trace levels of carbon monoxide can result in a significant decrease of oxygen available to the tissues. At the cellular level, the cyanide group binds oxidative enzymes and, thereby, prevents the uptake and utilization of oxygen available in the blood. Regardless of the level of the block in oxygen transport or utilization, however, asphyxia results in degraded tissue function and, if sustained, may result in irreversible tissue damage. The higher centers of the central nervous system are especially sensitive to this hypoxic effect.

- 2) Irritant. Any agent which produces an undesirable response of a tissue, but not necessarily one which results in tissue destruction. Both the response and tissue damage may vary with concentration. Internal organs may be irritated, but often the symptoms are not as specific as in external irritations.

- a) The effect may be one of local stimulation of function, local depression of normal function, local inflammation, or local sensory reaction.

- b) The tissues most frequently involved are the skin, mucous membranes, cornea, and the gastro-intestinal tract.

The primary effects may include itching, burning sensations of the eyes and/or respiratory tract, or skin or other local inflammation. Each of these effects may be accompanied by pain, annoyance, distraction, or a major psychological reaction or disruption. In addition, physiological stress reactions may be a secondary effect. Corneal irritation causes tearing and, consequently, a loss of visual functions and sensitivities. Severe respiratory irritation can result in pulmonary edema and a consequent asphyxiation. Reactions to skin irritations such as scratching and ulceration provide possibilities for infection and for the spread of the agent.

- 3) Toxicant. Any agent which produces either temporary or permanent interference with normal function. Toxicants which produce the most rapid effect and the greatest threat to survival of space crews are those which affect the central nervous system including consciousness. Asphyxiants, narcotics, and psychochemicals are of this sort. Manifest toxicity to other tissues may be less rapid, but eventually as damaging as that to the central nervous system, e.g., bone marrow damage, hepatic or renal dysfunction, etc. The most important effect is on the central nervous system. A critical criterion is loss of consciousness or a reduced level of alert functioning both of which may be a serious hazard. Toxicity to other organs may be less of a mission hazard; that is, it may permit completion of a mission, but then be followed by severe, though delayed, effects (e.g., on bone marrow, kidneys, etc.).

Processing of Toxic Agents by the Body

The time during which chemicals remain within the body depends on factors of absorption, elimination, storage, and biotransformation. The quantity of a chemical not essential to the normal functioning of the body but present in the tissues, is termed "the body burden". It is generally expressed in weight of substance (ug or mg) per unit weight (kg or per 100 grams) of tissue.

Absorption

Chemicals of immediate concern in space cabins enter the body principally through inhalation and skin absorption; oral ingestion is not as important. With inhalation, absorption is rapid and maximum blood levels are usually reached quickly. (Carbon monoxide is a classical exception.) Total quantity absorbed by this route is influenced by the rate and volume of respiration, the concentration of the contaminant, and the percentage extracted from the air. Experience has indicated the following contaminants have fairly easy access to the cell interior once they are absorbed into the body: gases, fat soluble compounds, organic bases, un-ionized combinations of weak acids. The following contaminants penetrate the cell membrane poorly; compounds with high water solubility, salts of organic basis, highly ionized compounds.

Storage

Chemicals entering through the lung are absorbed into the blood and distributed widely throughout the body. The site of maximum concentration generally depends on physical solubility and chemical reactivity of the absorbed substance. A great variety of chemical substances are stored in the body in trace amounts, frequently at levels which do not produce any known adverse effect. Metals that are bone-seekers remain in the body for years; chemicals that are non-reactive and fat soluble remain for months; however, the majority of substances are metabolized or excreted within hours or days.

Elimination

The principal routes of excretion are the expired air, urine, and feces. Less important, but not to be ignored, are the sloughed skin and perspiration. The more rapid the excretion, the less likely are toxic effects to occur.

Biotransformation

The majority of organic chemical substances are transformed by processes of oxidation, reduction, hydrolysis, and conjugation. These processes are termed biotransformations (230). The transformed substance may be more or less toxic than the original absorbed substance. There are frequently species, sex and age differences in the reactions, which make the extrapolation of animal data to man difficult.

Dose-Response Relationship

Quantitative relationship of dose and response are exceedingly important in the theoretical and practical evaluations of toxic action. In general, the greater the dose, the more severe the response or the more rapid is its onset. Time is an equally important factor in determining effect. In general, there are four possible relationships which can be expressed: (86)

- $E \sim C$; that is, the effect (E) is entirely due to the concentration (C). This condition probably never does exist in real situations where time, however short, is always involved.
- $E \sim Ct$, that is, the effect is the product of the concentration and the time (t) within certain limits. This relationship has been expressed as Haber's law:

$$C \times t^{(n)} = k \quad (10)$$

where n is an exponent which may itself change with time. This fact is most unfortunate in the complications which it presents in evaluating long missions with continually changing concentrations.

- $E \sim \frac{dC}{dT}$, that is, the effect is dependent on the rate at which the ingredient enters or leaves the cell.
- $E \sim (C-A)T$. In this equation the concentration in the body is corrected for the rate of biotransformation to more or less active substances (A).

Toxicity of Mixtures

Rarely are chemical toxicants present alone. In the problem of the space capsule, many hundreds may be present. The difficulty in evaluating the milieu of contaminants is the interaction which occurs due to the combined effect of these substances (170). In order to predict whether there is enhanced

or decreased effect, attention must be paid to the well-established phenomena of the combined effects of toxic substances which are:

Addition

An additive effect occurs when the fractions of the independently active components are equal to the effective dose of either alone. This can be expressed by the relationship for the TLV for additive components:

$$\frac{C_1}{TLV_1} + \frac{C_2}{TLV_2} + \frac{C_3}{TLV_3} + \dots + \frac{C_n}{TLV_n} = 1.0 \quad (11)$$

Potentiation

Potentiation is the enhanced effect from a combination of 2 or more substances, one of which shows no appreciable effects noted in the potentiation at any concentration. This may come about by the first sensitizing the point of action of the second substance or by decreasing the rate of its metabolic transformation.

Antagonism

Antagonism comes about by the nullification of the effect of one substance by another. There are generally three types: physiological, chemical, and competitive. Physiologic antagonism occurs when the chemicals act at different sites and produce opposite effects. Chemical antagonism results from the combination of one or more chemicals to yield an inactive form. Competitive antagonism implies competition for a single site of action for which both chemicals have an affinity.

Synergism

The joint action of two agents to give a combined effect greater than the algebraic sum of their individual effects is termed synergism. An equation similar to Equation (11) with a constant of <1 for synergism and >1 for antagonism may be used when the appropriate data are available.

Toxic Factors

In addition to the usual effects which may be predicted in the average individual, based on the observation of physiological, biochemical, and pathological changes which occur when sufficient doses of a toxicant are encountered, there are also unusual responses. These are unusual in that they occur generally at much lower doses than might be expected, require previous contact with the substance, or result in changes which are different from those normally expected.

Sensitization

This response, greater in magnitude than would be expected from known reactions to predicted doses, requires previous contact in order for it to occur. The theory is that an altered protein is formed by contact with an active chemical group. Subsequent contact with the offending agent will cause a release of antibodies which will result in local tissue changes of a shock-like nature. These may occur in the skin, respiratory tract, bone marrow, blood vessels, or general tissue structure.

Tolerance

With many chemicals, continuous or repeated exposure results in a progressive decrease in responsiveness and the dose necessary to elicit the response becomes greater. Mechanisms are related to an alteration in biotransformation and progressive desensitization of the responding organ.

Idiosyncratic Response

Adverse responses to extremely low doses of a chemical agent with manifestations of toxicity expected only at larger doses are termed idiosyncratic responses. The reason for this unusual susceptibility to the substance is not known. One cause is the lack, on a genetic basis, of particular detoxifying enzymes (196); another cause is the presence of increased end organ sensitivity for any one of several reasons.

Carcinogenesis

The development of neoplastic or cancerous tissue subsequent to the application of chemical agent is known as chemical carcinogenesis. Unlike other manifestations of toxicity which are universal from species to species and occur relatively close in point of time to exposure, carcinogens often show marked strain-specific sensitivity, have a prolonged latent period, and are not consistently related to dose.

Secondary Factors Modifying Toxic Action

A number of factors related to the external environment or the peculiarities of the test species modify the extent and threshold for toxic action.

Intrinsic Factors

The greatest single intrinsic factor influencing the response to a toxicant is the differences among species, although a ten-fold difference will often bracket the dose response for most species and man. Differences within the species may also account for ten-fold differences. Age modifies response, with great resistance occurring in the young adult and the greatest susceptibility found in the very young and very old. General physical condition and state of health determine responses, an adverse effect being seen in the less healthy state. Nutrition plays an important role and specific dietary deficiencies

may modify susceptibility. Tolerance developed to a particular agent may bring about resistance to progressively larger amounts of the agent.

Extrinsic Factors

The number and spacing of the doses, time of exposure, particle size and surface area of particulates, together with the total quantity administered, are the most important factors. The route of administration sometimes alters the response, as does the physical state of the substance and its degree of chemical reactivity as determined by solubility. Environment conditions such as state of nutrition temperature, pressure, and the presence of other chemical substances are important modifying factors, especially in the space cabin environment.

TOXICOLOGY IN THE SPACECRAFT ENVIRONMENT

In the context of cabin exposure, one is dealing with a toxicological problem involving the prediction of probable responses to a low level, continuous exposure to a mixture of chemicals, some of which are not as yet known. There is a constantly changing environment with each compound building up to equilibrium levels in variable periods of time. Programmed or accidental cabin depressurizations can cause sudden purges and reduction of concentration level to zero allowing excretion of the compound; then follows rebuildup in the body to a new equilibrium. There is simultaneous adaptation or desensitization and variable levels of cross tolerance between compounds (170). Cumulative effects under such a variable exposure background are most difficult to assess.

In order to set exposure limits in space operations, one must convert the usual industrial TLV values (TLV_{ind}) for 8 hrs/day, 5 days per week exposure to TLV values for continuous exposure in space (TLV_{space}). Experience with submarines has required extrapolation of industrial TLV data to 90 days continuous exposure (27, 151, 155, 187). At the industrial threshold limit and under normal conditions, continuous toxicity tests on animals for 90 days have shown evidence of a wide variation in safety factors of present threshold limits. These tests showed effects ranging from no mortality or other untoward effects, to moderate toxicity, to almost complete lethality in animals tested over 90 days at the threshold limit. It should be noted that taking animal responses to continuous exposure as a measure of the safety factor magnitude for intermittent exposure may not be entirely correct in all instances; all substances are not cumulative either in amount or in effect on continuous exposure. The technique does provide a rough estimate of the safety factor.

The following equation has been proposed: (200)

$$TLV_{space} = \frac{TLV_{ind} \times F_{press}}{F_{cont} \times F_{temp} \times F_{rm} \times F_{O_2} \times F_{fat} \times F_{int}^*} \quad (12)$$

where $F_{\text{press}} = \text{Dosage factor from ambient pressure change to 5 psi} = 3$

$F_{\text{cont}} = \text{Toxicity factor from continuous dosage} = 1 \text{ to } 4$

$F_{\text{temp}} = \text{Toxicity factor from temperature change, } F_{\Delta T}$

$F_{\text{rm}} = \text{Toxicity factor due to restricted motion, } F_{\Delta M}$

$F_{\text{O}_2} = \text{Toxicity due to 100\% O}_2 \text{ at 5 psi}$

$F_{\text{fat}} = \text{Toxicity factor due to fatigue, } F_{\Delta F}$

$F_{\text{int}}^* = \text{Toxicity factor from interaction of the factors} = f_1 \times f_2 \times f_3 \dots f_n$

and where

$f_1 = \text{toxicity above that from intermittent 8-hr exposure and that from 3-fold the dose}$

$f_2 = \text{toxicity from combination of O}_2 \text{ toxicity and toxic substance}$

$f_3 = \text{toxicity from effect of O}_2 \text{ on fatigue}$

Since the space cabin atmosphere, in the near future at least, will range from 5 to 7 psia, the $F_{\text{press}} = 3$ appears adequate to cover the fact that lung absorption of gases is by simple diffusion and accordingly is directly proportional to external pressure (163). As mentioned above, the multiplication of 8 hr/day data for 5 day week by 3 does not give adequate safety in all cases for 24 hr/day continuous exposure. The elusive metabolic interactions determining this exact multiplication factor have been discussed above and elsewhere (71, 200). The usual Q_{10} factor indicates that for every 10°C rise in temperature the metabolic rate of a cell will increase at least 2-fold. Although in general, toxicity increases roughly by this factor as body temperature increases, it is by no means a universal rule (100). The restriction of movement and fatigue may add further stressful conditions to the environment and alter to an as yet unknown degree, the response to some toxic agents in humans (144, 200).

The effects of 5 psia, 100% oxygen may have a profound effect, especially on those agents which can inactivate the anti-oxidant defenses (2, 160, 161). Reduction of tocopherol in the plasma of Gemini astronauts has been reported along with a hemolytic process which may resemble the anemia of acanthocytosis (159). (See Nutrition, No. 14, and Oxygen-CO₂-Energy, No. 10.)

There is some indication in animals that oxygen at 5 psia will synergize with systemic toxic agents such as CCL₄ (122, 194, 203). Species differences are quite marked with the primates being relatively resistant. The synergistic factors for specific agents in humans are still not known. Recent evidence suggests that unknown toxic factors may be present in test chambers or associated with such atmospheres as 70% oxygen-30% nitrogen at 5 psia in the presence of a normal alveolar P_{O_2} (202).

The interaction factors $f_1 \rightarrow f_n$ are still not clear. The studies of 90 day TLV suggest factors in the range of 2 to 4 of f_1 for some agents. For toxic materials with hemolytic potential f_2 may be as high as 2, and for antioxidants, as low as $1/3$. Since there is no evidence that oxygen has a profound effect on fatigue, f_3 will probably be rather close to unity (17, 81, 161).

Calculation of TLV_{space} for 11 compounds by this approach leads to ratios of TLV_{Ind} of TLV_{space} : about 3 to 50 (200). Similar calculations have been made for 95 compounds with this ratio running from 1:1 to 10:1 (86). About $1/2$ of the compounds had ratios of 2 to 5:1.

SOURCE OF CONTAMINANT

The sources of contaminants in space operations are man and his activities, materials and outgassing, equipment and processes, and finally, malfunctions and emergencies. Table 13-16 lists those compounds found in space cabins, simulators, submarines, and underwater laboratories.

Human Sources of Contaminants

Principal sources of contaminants from man are expired air, urine, feces, flatus, and perspiration (125, 165, 189, 220). The data presented below can be used for waste management analysis.

The primary components of expired air influencing toxicity are CO_2 , H_2O , and carbon monoxide from porphyrin metabolism (188, 206). The excretion of water in sweat, respiration and urine of man has been covered in Water, (No. 15).

The composition and daily output of urinary components are summarized in Table 13-3a.

The composition and daily output of fecal components are summarized in Table 13-3b. The weight of feces on mixed diets varies from 0.13 to 0.5 lbs/day wet weight (160 to 250 gm/day and from 0.06 to 0.17 gm/day dry weight (25-75 gm/day (165). The higher the vegetable content, the higher the weight of fecal residue.

Table 13-4 presents the amino- and fatty acid residues of feces.

Figure 13-5 presents caloric output in feces, gaseous elaboration of stored feces, and flow rates of urinary output.

Table 13-6 represents the flatal output of man under different conditions. The nitrogen data represents all materials not included in tests for the other gas. Traces of carbon monoxide are present in this fraction.

The composition of typical sweat output depends on state of acclimatization of man (11). Table 13-7 presents the range of output.

Table 13-3
Composition of Human Urine and Feces
(After Roth⁽¹⁶⁵⁾)

a. Urine

Urine has a specific gravity of 1.002 to 1.035 and a pH of 4.6 to 8.0. The solid contents shown in the table are recorded as mg/24 hours.

	Mean Values					Range
	Altman and Dittmer, eds. (4)	Long (116)	Sunderman and Boerner (201) 60,000.	Hawk and Bergheim (82) 60,000.	Diem, ed. (47)	
Solids						55,000-70,000
Electrolytes						0.049-0.112
Aluminum	.077	.078	-	-	-	0-0.091
Arsenic	.0231	-	-	-	-	35-840
Bicarbonate	140.0	-	-	-	-	0.840-7.70
Bromine	-	2.1	-	-	-	43.0-581.0
Calcium	231.0	-	-	200.0	-	7,600-15,000
Chloride (as NaCl)	12,000.	-	-	-	7,638.	2,800-12,600
Chlorine	7,000.	-	-	-	0.018	0-0.049
Copper	0.035	-	-	-	-	0.30-7.0
Fluorine	1.540	-	-	-	-	0.007-0.490
Iodine	-	-	-	-	0.045	0.02-1.1
Iron	0.490	-	-	-	-	0.004-0.15
Lead	0.028	0.035	-	-	-	29.4-307
Magnesium	94.5	-	-	150.	103.	0.007-0.098
Manganese	-	-	-	-	-	0.140-0.280
Nickel	-	0.15	0.15	-	-	700-1,600
Phosphorus (as P)	-	-	-	1,100.	1,100.	700-1,300
Inorganic	840.	-	-	-	-	6.23-13.09
Organic	9.17	-	-	-	-	1,120-3,920
Potassium	2,380.	-	-	2,000.	2,740.	0-0.140
Selenium	0.035	-	-	-	-	420-14.0
Silicon	9.10	-	-	-	-	1,750-6,580
Sodium	4,200.	-	-	4,000.	4,615.	357-3,400
Sulfur, total	1,120.	-	-	1,000.	-	245-2,700
Inorganic	777.	-	-	800.	-	40-300
Ethereal	66.5	-	-	-	-	73-400
Natural	133.	-	-	120.	-	80-300
Conjugated	-	-	-	80.	-	.0091-.0175
Tin	-	-	-	-	0.457	.110-.500
Zinc	.364	-	-	-	-	
Nitrogen compounds						1.1-1.7
Adenine	1.40	1.4	-	-	-	2.8-40
Allantoin	11.9	-	-	40.	-	1,100-2,800
Amino Acids, Total	-	-	1,100.	-	-	500-1,400
Free	-	-	500.	-	-	21-71
Alanine, Total	38.5	46.	-	-	-	8-11
Amino-adipic acid	-	10.	-	-	-	Traces-10
Amino-butyric acid	-	10.	-	-	-	4-180
Amino-isobutyric acid	-	20.	-	-	-	5-7
Anserine	-	-	-	-	-	<10-56.8
Arginine, Total	31.5	<10.	23.7	-	47.0	34-99
Asparagine	-	54.	-	-	-	<10-258.8
Aspartic acid, Total	119.0	<10.	164.5	-	113.4	2-3
Carnosine	-	-	-	-	-	0-196.0
Citrulline	63.0	10.	-	-	-	10-200
Crystine, Total	119.0	10.	-	-	87.7	<10-484.7
Glutamic acid, Total	-	<10.	351.4	-	249.9	-
Glutamine	-	100.	-	-	-	132-670.6
Glycine, Total	455.0	132.	-	-	405.0	65.4-498.8
Histidine, Total	189.0	216.	203.3	-	284.0	<10
Hydroxylysine	-	<10.	-	-	-	0.26-1.4
Hydroxyproline, Total	1.40	0.51	-	-	23.05	6.5-33.4
Isolericine, Total	14.0	18.	20.3	-	11.3	11.9-40.0
Leucine, Total	21.0	14.	21.2	-	27.9	7-166.0
Lycine, Total	56.0	19.	73.2	-	102.0	3.8-15.0
Methionine, Total	9.8	10.	8.6	-	6.6	47-384
1-methylhistidine	-	180.	-	-	-	-
3-methylhistidine	-	50.	-	-	-	<10-10.5
Ornithine	10.5	<10.	-	-	-	

Table 13-3 (continued)

a. Urine (continued)

	Mean Values					Range
	Altman and Dittmer, eds. (4)	Long (116)	Sunderman and Boerner (201)	Hawk and Bergheim (82)	Diem, ed. (47)	
Amino Acids (cont.)						
Phenylalanine, Total	21.0	18.	23.3	-	28.7	9-45.4
Proline, Total	42.7	<10.	42.8	-	43.3	<10-63.0
Sarcosine	-	<10.	-	-	-	<10
Serine, Total	42.0	43.	-	-	-	27-73
Taurine	-	156.	-	-	156.	7.7-294
Threonine, Total	35.0	28.	53.8	-	83.2	14.8-182.0
Tryptophan, Total	28.0	-	41.4	-	22.9	8-86.1
Tyrosine, Total	49.0	35.	52.5	-	55.5	15-103.3
Valine, Total	21.0	<10.	19.8	-	30.1	<10-44.7
Ammonia	-	700.	-	-	-	300-1,100
Bilirubin	49.0	-	-	-	5.	5-49.0
Coproporphyrin I & III	-	-	-	-	-	.0168-0.280
Creatine	56.0	-	-	-	-	0-800
Creatinine	1,610.0	-	-	1,200.	2,145.0	1,000-3,219
Ethanolamine	-	12.2	-	-	-	4.8-22.9
Glycocyamine	-	-	-	-	-	21-67
Guanidine	-	-	-	-	-	10-20
Guanidinoacetic acid	-	-	-	-	30.	14.0-35.0
Guanine	0.42	1.6	-	-	-	0.21-2.0
8-Hydroxy-7-methyl	1.40	1.6	-	-	-	1.1-2.0
7-Methyl	6.30	6.5	-	-	-	5.5-7.8
N ² -Methyl	0.490	0.5	-	-	-	0.4-0.6
Hippuric acid	-	-	-	700.	700.	70-2,500
Histamine	-	-	-	-	-	0.014-0.070
Hypoxanthine	9.80	9.7	-	-	-	5.6-13.3
I-Methyl	0.42	0.4	-	-	-	0.2-0.7
Imidazole derivatives	-	-	-	-	286.1	140.0-300.0
Indoxylsulfuric acid	70.	100.	0	10.	-	5-160.0
Lipoproteins	-	23.5	-	-	-	-
Methionine sulfoxide	-	-	-	-	-	0-21.70
Nitrogen						
Total N	-	-	-	-	15,300.	1,000-21,000
Amino Acid N	-	-	-	200.	349.	100-431
Ammonia N	-	-	-	700.	-	210-1,000
Protein	-	-	-	-	<50.	2.10-80
Albumin	-	-	-	-	-	10-100
Purine bases	-	-	10.	-	-	0.01-70.0
6-Succinopurine	0.980	-	-	-	-	-
Urea	-	22,000.	30,000.	-	-	14,000-35,000
Uric acid	140.0	567.0	-	700.	528.	56-1,000
Urobilin	-	-	-	-	-	10-130
Urobilinogen	-	-	-	-	-	0-25.0
Uropepsin(as tryrosine)	-	-	-	-	417.	98-835
Xanthine	6.30	6.1	-	-	-	4.90-8.6
Vitamins						
B ₁ (thiamine)	0.21	-	-	-	-	0.042-0.420
B ₂ (riboflavin)	0.868	-	-	-	-	0.140-1.680
B ₆ (pyridoxine)	-	-	-	-	-	.0056-.1890
B ₁₂ (cyanocobalamin)	30.8 x 10 ⁻⁶	31.	-	-	-	16.1x10 ⁻⁶ -55.3x10 ⁻⁶
B _c (folic acid)	.00406	-	-	-	-	.0021-0.238
B _x (p-aminobenzoic acid)	-	-	-	-	-	0.140-0.210
C (ascorbic acid)	-	-	-	-	-	5-55
H (biotin)	0.035	-	-	-	-	0.014-0.070
Choline	5.53	-	-	-	-	4.76-9.10
Citrovorum factor	.00259	-	-	-	-	.00161-.00483
Inositol	14.0	-	-	-	-	8-144
Niacin	0.238	-	-	-	-	0.140-1.40
Niacinamide(nicotinamide)	1.40	-	-	-	-	0.70-3.50
Pantothenic acid	3.15	-	-	-	-	1.12-7.0
Dehydroascorbic acid	-	5.1	-	-	-	5.1-20.3
Dehydroascorbic + diketogulonic acid	16.1	-	-	-	-	0-89.6

Table 13-3 (continued)

a. Urine (continued)

	Mean Values					Range
	Altman and Dittmer, eds. (4)	Long (116)	Sunderman and Boerner (201)	Hawk and Bergheim (82)	Diem, ed. (47)	
Vitamins (cont.)						
Diketogulonic acid	-	-	-	-	-	9.8-13.30
N'Methylnicotinamide	-	-	-	-	-	2.80-42.0
Pyridoxal	0.07	-	-	-	-	0.49-0.371
Pyridoxamine	0.112	-	-	-	-	0.028-0.210
4-Pyridoxic acid	-	-	-	-	-	0.63-11.20
Trigonelline	-	-	-	-	-	2.10-21.0
Acids						
Acetoacetic acid	2.80	-	-	-	-	2.10-4.20
Carbolic (phenol) Total	-	-	-	-	-	14.0-42.0
Free	-	-	-	-	-	0-3.50
Carbonic acid	189.0	-	-	-	-	147.0-231.0
Citric acid	-	-	-	-	678.	128-1,400
Formic acid	56.0	-	-	-	-	28.0-140.0
Glucuronic acid	-	-	-	-	-	100-1,325
m-Hydroxybenzoic acid	-	-	-	-	-	10-16
m-Hydroxyhippuric acid	-	4-6	-	-	-	2-150
p-Hydroxyphenyl- hydroacrylic acid	-	10.	-	-	-	2-150
Lactic acid	210.0	73.	-	-	-	50-600.0
Oxalic acid	35.0	22.	-	20.	-	1-49.0
Oxoglutaric acid	-	22.	-	-	-	20-40
Pyruvic acid	-	-	-	-	100.	2.5-100
Misc. organic compounds						
Acetone bodies, Total	14.0	-	-	-	19.4	2.10-23.5
Amylase (somogyi)	-	-	-	-	-	260-950 units
Cholesterol	-	-	-	-	-	0-4.998
Glucose (true)	-	-	-	-	72.	50-300
Ketones (total)	-	-	-	-	50.5	19.8-81.2
Phenols	-	-	-	200.	437.	200-636
Reducing substances	-	-	-	-	-	490-1,500
Glucose	-	4.3	-	-	-	1-12
Fructose	-	5.	-	-	-	0-5
Arabinose	mgm per	1.5	-	-	-	0-3
Ribose	100 ml.	18.7	-	-	-	-
Xylose	-	1.0	-	-	-	0-3
Lactose	-	7.	-	-	-	0-10
Sucrose	-	5.	-	-	-	0-5
Hormones						
Adrenalin	-	.005	-	-	-	.0006-.0115
Aldosterone	.0035	-	-	-	-	.0007-.0091
Androgens	18.20	-	-	-	-	14.0-23.1
Androsterone	3.5	-	-	-	-	2.45-420
Catecholamines (total)	-	.082	-	-	-	.25-.150
Estradiol	-	.002	-	-	-	0-.007
Estriol	-	.006	-	-	-	.001-.012
Estrone	-	.006	-	-	-	0-.011
Etiocanolone	3.5	-	-	-	-	2.45-4.20
Hydroxysteroids	5.6	-	-	-	-	2.8-11.9
Insulin	-	-	-	-	-	(0.16-0.4 units)
17-ketogenic adreno- corticoids	14.7	-	-	-	-	10.5-21.7
α -Ketol-steroids	18.2	-	-	-	-	9.1-32.9
Melanocyte stimulating hormone	-	(27.7 units)	-	-	-	(7.5-47.5 units)
Noradrenalin	-	0.027	-	-	-	.015-.050
Parathyroid	-	(60 units)	-	-	-	(47-72 units)
Pregnanediol	0.91	-	-	-	-	0.35-1.40
Tetrahydrocortisol	1.68	-	-	-	-	0.56-3.50
Tetrahydrocortisone	3.78	-	-	-	-	1.40-8.40

Table 13-3 (continued)

b. Feces

The water content of feces ranges between 65 and 85%, and the pH from 6.9 to 7.7. The bulk and solid contents shown in the table are recorded in mg/24 hours unless otherwise noted.

	Mean Values					Range**
	Altman and Dittmer, eds. (4)	Diem, ed. (47)	Sunderman and Boerner (201)	Spector, ed. (195)	Goldblith and Wick (71)	
Bulk	-	-	-	-	150,000	50,000-350,000
Dry matter	-	-	-	-	27,000	23,500-35,000
Electrolytes						
Aluminum	.0428	-	-	-	-	.0428-2.9
Arsenic	2.353	-	-	-	-	.071-8.27
Calcium	534.0	640.	640.	549.	1,180.	100.0-1,180
Chloride	-	90.	-	-	-	14.87-35.65
Cobalt	.0005	-	-	.0005	1.400	.0001-1.400
Copper	1.925	-	-	1.940	1.020	1.020-2.638
Iron	8.556	-	-	8.640	28.80	4.6-100.0
Lead	0.299	-	-	-	-	0-400
Lithium	-	-	-	-	2.600	-
Magnesium	178.2	200.	200.	180.	252.	107-252
Manganese	-	-	-	4.760	3.430	1.283-8.556
Mercury	.001	-	-	-	-	-
Molybdenum	-	-	-	-	-	2-4
Nickel	-	-	-	0.130	2.900	.0856-10.0
Phosphorus	703.0	510.	-	-	-	506.2-1700
Potassium	470.	470.	470.	482.	291.	281-1037
Silver	.0570	-	-	-	-	-
Sodium	121.2	120.	120.	122.	116.	116-122
Strontium	-	-	-	-	0.390	-
Sulfur, total	142.7	130.0	-	-	-	-
Tin	-	-	-	-	-	0.5-32.09
Zinc	7.130	-	-	-	-	4.135-10.27
Nitrogen compounds						
Arginine	-	-	-	-	-	1200-2100
Bile pigments	-	-	-	-	150.	-
Histidine	-	-	-	-	-	600-800
Indole	90.	-	-	-	-	60-100
Isoleucine	-	-	-	-	-	1400-2300
Leucine	-	-	-	-	-	1800-2900
Lysine	-	-	-	-	-	1900-2900
Methionine	-	-	-	-	-	500-800
Nitrogen, total	-	-	-	-	1500.	700-2100
Threonine	-	-	-	-	-	1400-2200
Urobilinogen	-	10.	-	-	101.	10-280
Valine	-	-	-	-	-	1500-2600
Misc. organic compounds						
Carbohydrates & derivatives:						
Total reducing sugar	-	-	-	-	-	-
Fiber*	-	-	-	-	-	10-30
Fats & derivatives:						
Total fat	-	-	-	-	4500.	1000-7000
Total fat*	-	-	-	-	-	10-25
Total fat (unsaponifiable)*	-	-	-	-	-	0-5
Vitamins						
Vitamin A	-	-	-	-	-	0.17-0.33
p-Aminobenzoic acid	-	-	-	-	0.246	-
B vitamins	-	-	-	-	15.	-
Vitamin B ₂ (uroflavin)	1.029	-	-	-	-	0.823-1.313
Vitamin B ₆	-	-	-	-	-	0.5-0.8
Biotin	-	-	-	-	0.133	.1-2
B-carotene	-	-	-	-	-	1.7-3.3
Vitamin E	21.	-	-	-	-	-
Folic acid	-	-	-	-	0.304	-
Pantothenic acid	-	-	-	-	2.20	1.8-3.8
Pyridoxin	-	-	-	-	0.38	0.1-0.5
4-pyridoxic acid	-	-	-	-	-	0.5-0.6
Nicotinic acid	-	-	-	-	3.63	3.5-5.5
Thiamine	-	-	-	-	0.548	0.2-0.8
Riboflavin	-	-	-	-	1.029	0.4-1.20

* Per cent of dry weight.

** Extreme values include data of Consolazio, et al. [14].

Table 13-4
Amino and Fatty Acids in Feces
 (After Roth⁽¹⁶⁵⁾, adapted from Goldblith and Wick⁽⁷¹⁾)

a.

Amino Acid in Fecal Protein

Data recorded as grams of amino acid/16 grams of N

<u>Amino Acids</u>	<u>Determined by Microbiological Assay</u>	<u>Determined by Amino Acid Analyzer</u>
Alanine	-	4.8
Arginine	5.7, 5.7	3.2
Aspartic acid	-	8.5
Cystine	0.60, 0.60, 0.64	-
Glycine	-	3.3
Glutamic acid	-	4.4
Histidine	2.5, 2.5	1.7
Iso-Leucine	6.3, 6.3	3.6
Leucine	7.9, 7.8, 7.3	5.7
Lysine	8.0, 8.7	5.1
Methionine	2.6, 2.7	1.9
Phenylalanine	4.7, 4.7	3.3
Proline	-	3.7
Serine	-	2.8
Threonine	3.7, 3.9	3.3
Tryptophan	0.71, 0.67	-
Tyrosine	1.9, 1.9	3.2
Valine	8.3, 8.8	4.3

b.

**Comparison of Composition of Bound, Free, and Total Fatty Acids
 in Fecal Lipid for a Normal Human**

Percentage of Acids in C₆ - C₂₀ Range

<u>Acid**</u>	<u>Free</u>	<u>Bound</u>	<u>Total</u>	<u>Acid**</u>	<u>Free</u>	<u>Bound</u>	<u>Total</u>
10:0	0.6	0	0.3	10-Hydroxy 18:0	0.7	0.9	0.8
12:0	4.3	2.2	3.3	14:1	0	0	0
14:0	8.9	4.4	6.6	16:1	1.4	2.1	1.8
Branched 15:0	0.7	1.1	0.9	18:1	6.8	10.7	8.7
15:0	1.4	1.1	1.2	Isomer 18:1	3.5	6.5	5.0
16:0	55.2	35.3	45.2	18:2	1.3	2.8	2.0
Branched 17:0	0.9	1.4	1.2	18:3	0	0	0
17:0	0.4	0.8	0.6	20:3	Trace*	Trace*	Trace*
18:0	12.9	31.8	22.3	20:4	Trace*	Trace*	Trace*
				Other unsatu- rated C ₂₀ acids	Trace*	Trace*	Trace*

*Trace indicates less than 0.5%.

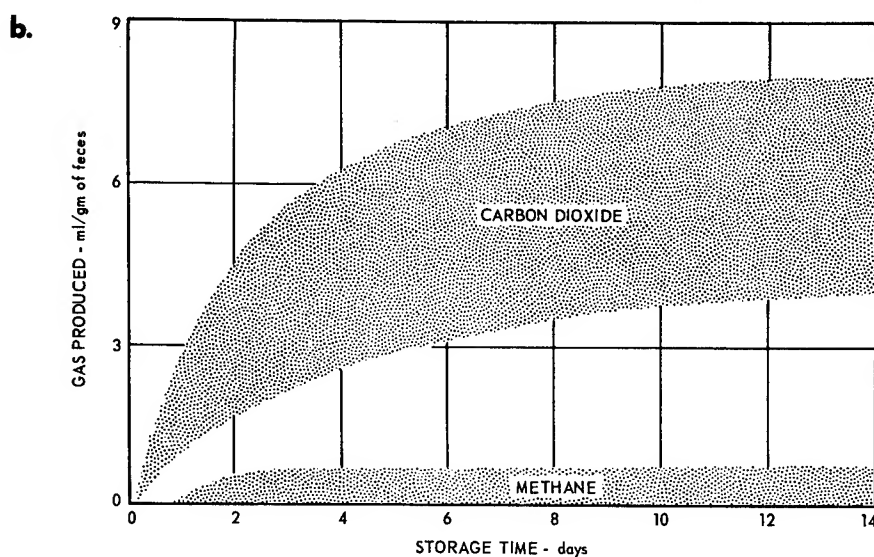
**Number of carbons and double bonds.

Table 13-5
Physical Data: Feces and Urination

a. Caloric Value of Feces

	<u>Mean Value</u>	<u>Range</u>
Kcal excreted/day	104	70-142
Kcal/gram, dry weight	4.26	3.48-5.09

(After Wollaeger et al⁽²³¹⁾)



The shaded areas define the ranges of values for the two major gases produced when feces are stored at 86°F (30°C) for a period of two weeks. Some specimens produced traces of hydrogen and hydrogen sulfide as well.

(After Wheaton et al⁽²²⁸⁾)

c. Volume, Maximum Rate, and Duration of Urine Flow
During the Act of Urination in Adult Men

<u>Subjects</u>	<u>Volume (ml)</u>		<u>Duration (sec)</u>		<u>Maximum rate (ml/sec)</u>		<u>Time to reach maximum rate initially (sec)</u>		<u>Source</u>
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	
28 adult males 82 test runs	269	65-580	21	9-47	22	5-40	5.7	1-12	Grace et al [22]
141 adult males, bladder vol. >200 ml.	-	-	-	-	-	13-45	-	-	Holm [30]
	310	-	-	-	20	-	-	-	Ross [48]
	520	-	-	-	24	-	-	-	Ross [48]

(After Roth⁽¹⁶⁵⁾)

Table 13-6
Generation and Composition of Flatus
(After Roth⁽¹⁶⁵⁾, adapted from Kirk⁽¹⁰⁴⁾)

a. Flatus Generation *			
Specimen	Volume		Source
	Mean ml/day	Range ml/day	
Estimated average volume of discharged gas	1000	-	Clemedson [12]
Discharged gas; 47 normal individuals on ordinary (cabbage free) diet. Single emissions ranged between 25 and 100 ml.	825	100-2800	Kirk [34]
Single discharge 50-500 ml.	1000	-	Fries [19]
Normal average quantity passed daily; five subjects.	524	-	Beazell [6]
Five male medical students unbothered by flatulence; quantities equally divided between day and night.		380-655	Davenport [15]
From control volume of 17 ± 10 cc per hr. to 203 ± 87 cc per hr. for five men changing from control volume to a pork and beans or dried lima bean diet; (25-50% of calorie intake) for two weeks.		240-4872	Davenport [15]
	2000		Mattoni [39]

* Emitted flatus, not gas formed in stomach, small intestine, or colon; not eructed gas.

b. Chemical Composition of Flatus*				
	Cabbage Free Diet, 1943-44 20 individuals		Cabbage & Milk Free Diet, 1945-46 25 individuals	
	Mean %	Range %	Mean %	Range %
Carbon dioxide	9.0	1.2-15.0	9.7	0.7-24.7
Oxygen	3.9	0.0-15.7	5.5	0.5-20.0
Methane	7.2	0.0-30.3	3.1	0.0-21.4
Hydrogen	20.9	3.1-34.0	12.0	0.4-36.5
Nitrogen	59.0	39.7-88.2	70.0	24.7-87.7
Hydrogen sulfide	.0003	0.0-.0017	.0002	0.0-.0003

*Samples obtained by rectal catheterization.

Table 13-7

Composition of Sweat

(After Roth⁽¹⁶⁵⁾, adapted from Altman and Dittmer, eds.⁽⁴⁾ and Spector, ed.⁽¹⁹⁵⁾)

	Mean	Range
	mg/100 ml of sweat	
Water	-	99.0-99.5%
Solids, total	-	1.174-1.597%
Electrolytes		
Calcium	2.1	1-8
Chloride	-	30-468
Copper	0.006	0.006-7.5
Iodine	0.0009	.0005-.0012
Iron	0.027	.022-0.2
Magnesium	0.2	.004-4.5
Manganese	0.006	.002-7.4
Phosphorus	0.5	.003-2.0
Potassium	-	21-126
Sodium	-	24-312
Sulfur	-	0.7-7.4
Nitrogen Compounds		
Amino Acids		
Arginine	13.6	5.8-21.4
Histidine	8.	4.25-14.00
Isoleucine	2.27	1.0-3.73
Leucine	2.69	1.2-4.2
Lysine	2.26	1.4-3.38
Phenylalanine	2.19	1.0-3.5
Threonine	5.38	1.7-9.1
Tryptophan	1.12	0.4-1.85
Tyrosine	3.15	1.2-5.45
Valine	2.96	1.5-4.5
Creatinine	-	0.1-1.3
Urea	-	12-5.7
Uric Acid	0.16	0-2.5
Nitrogen		
Total N	33.2	27-64
Non-protein N	31.	27-64
Amino acid N	2.8	1.1-10.2
Ammonia N	-	2.5-35.0
Urea N	-	5-39
Misc. organic compounds		
Ascorbic acid	-	0-.002
Carbolic acid (phenol)	-	2-8
Lactic acid	-	45-452
Corticoids	-	.004-.008
Sugar (as glucose)	-	0.1-40
Vitamins		
B ₁ (thiamine)	.00015	0-.006
B ₂ (riboflavin)	.0005	.0-.0005
B ₆ (pyridoxine)	-	.0004-.00017
B ₁₂ (folic acid)	.0006	.00053-.00088
B _x (p-aminobenzoic acid)	.00024	.00008-.00170
C (as dehydro-ascorbic acid)	.0705	
Choline	.0071	.0003-.0071
Inositol	.021	.015-.036
Niacin (nicotinic acid)	-	.0017-.022
Pantothenic acid	.0038	.0015-.0077

The range of saliva output in resting, unstimulated man is 42 to 83 ml/hr (47). When stimulated by chewing paraffin, the output may be raised to about 190 ml/hr with some individuals reaching up to 300 ml/hr (116, 219).

The composition of saliva is noted in Table 13-8.

Data on the generation of hair is noted in Table 13-9a and the composition of hair is noted in Table 13-9b. Differences in composition vary with hair color and race. The generation and composition of nails is noted in Table 13-10; and the generation and composition of skin and sebum, in Table 13-11. The composition of skin secretions are noted in Figure 13-12.

The composition of tears and wax are noted in Figure 13-13. The composition of semen is available (165).

Table 13-14a presents the total waste accumulated from humans per man/day. Data for waste output after prototype Apollo nominal and contingency diets are presented in Figure 14-14b. A list of human effluents according to chemical grouping has also been compiled as shown in Tables 13-14b and c.

Cooking may release such toxic materials from foods themselves (43) or conversion products such as acrolein and formaldehyde. Toiletry, soaps, and hair tonics are also sources of ethereal compounds to be avoided. Micro-organisms from humans will be covered below.

Materials and Machines

Compounds of relatively high vapor pressure are outgassed from solid materials and from the hydrocarbon lubricants and operating fluids of machines. They originate from such sources as plastics, toilet articles, lubricating compounds, insulations, paints, cements, and residual solvents from degreasing treatments. Aliphatic and olefinic hydrocarbons may originate as impurities in breathing oxygen. The presence of these compounds in compressed gases stems from the cracking of hydrocarbon compressor oils. The various Freons and Coolanols are used as refrigerants or are present as impurities in refrigerants.

Lists of non-metallic materials currently being used in manned spacecraft are available at the NASA Manned Spacecraft Center in Houston, Texas (72, 79). Agents used in plastic manufacture are also available (131).

The rate of outgassing for various spacecraft materials is under study (57, 90, 141, 149, 203-205). Unfortunately, the oxygen content and temperature of the atmosphere alters the rate and nature of gas-off products. Intermittent purging of the atmosphere is also a variable to be considered in this regard. Compounds continue to be outgassed after 90 days (203).

Table 13-15 lists in alphabetic order chemicals or chemical groups which have been identified as contaminants associated with Projects Gemini and Mercury or with the nuclear submarine environment (173, 212) or anticipated as an agent from fire or other emergencies. Unless otherwise stated, the

Table 13-8
Composition of Saliva
(After Roth⁽¹⁶⁵⁾)

All data recorded as mg/100 mg of saliva unless otherwise noted.

	Mean Values		Range
	Diem, ed. (47)	Altman and Dittmer, eds. (4)	
Water	95.5		
Total solids	-	581.0 (P)*	386-860 (P)
Electrolytes			
Bicarbonate	-	39.294	21.228-65.27
"	-	96.014 (P)	49.532-118.767 (P)
Bromine	-	-	0.02-0.71
Calcium	-	5.8	4.5-10
"	-	5.5 (P)	3.5-9.2 (P)
Carbon dioxide	-	12.	5-25 (vol %)
"	-	25. (P)	8-44 (vol %) (P)
Chloride	102.8	60.025	40.4-165.2
"	-	41.89 (P)	41.89-62.835 (P)
Cobalt	.00704	.00244 (P)	0-.01253 (P)
Copper	.0256	.0063	.002-.0256
"	-	.0259 (P)	.010-.0475 (P)
Fluorine	-	-	.010-.020
Iodine	-	-	0-.350
Magnesium	-	1.409	.3888-2.576
Phosphorus, total	20.4	24.4	12.0-28.8
Organic	5.5	5.5	0-13.3
Inorganic	14.9	14.9	7.4-21.7
Potassium	77.0	80.3	46.4-148
"	-	78.0 (P)	50-95
Sodium	-	23.2	8-56
"	-	57.3 (P)	19-133
Sulfur	7.6	-	-
Thiocyanate	-	13.4	3.1-33.0
Nitrogen compounds			
Ammonia	-	4.42	2-10
"	-	5.95 (P)	1.56-12.07
Amino acids			
Alanine	-	1.2	0.5-2.9
Arginine	-	-	3.3-10.0 (P)
Aspartic acid	-	0.15	0.13-0.33
Cystine	-	-	0.16-0.45 (P)
Glutamic acid	-	1.2	0.5-1.3
Glutamic acid	-	-	3.0-12.6 (P)
Glycine	-	1.4	0.5-3.6
"	-	-	1.9-15.5 (P)
Histidine	-	-	0.35-2.00 (P)
Isoleucine	-	-	0.2-0.9 (P)
Leucine	-	-	0.025-0.300 (P)
Lycine	-	0.7	0.15-1.50 (P)
"	-	-	0.4-1.5 (P)
Methionine	-	-	0.005-0.010 (P)
Phenylalanine	-	-	0.6-2.5 (P)
Proline	-	-	0.35-1.50 (P)
Serine	-	0.66	0.33-1.20
"	-	-	1.0-1.8 (P)

*(P) Paraffin stimulated saliva

Table 13-8 (continued)

All data recorded as mg/100 mg of saliva unless otherwise noted.

	Mean Values		Range
	Diem, ed. (47)	Altman and Dittmer, eds. (4)	
Nitrogen compounds (cont.)			
Threonine	-	-	0.4-5.6 (P)*
Tryptophan	-	-	0.2-0.9 (P)
Tyrosine	-	-	0.2-1.0 (P)
Valine	-	-	0.7-2.2 (P)
Creatinine	-	0.35 (P)	0.275-0.455 (P)
Histamine	.01456	-	.01065-.01810
Mucin	-	250.	80-600
"	-	270.	-
Nitrogen			
Total nitrogen	-	90.0 (P)	36.1-125.3 (P)
Ammonia nitrogen	-	3.8	0.5-9.9
Non protein nitrogen	-	36.4	8.2-62.4
Protein nitrogen	-	63.6 (P)	22.9-88.2 (P)
Protein, total	262.	386.	0-630
"	-	242. (P)	140-527 (P)
Urea	-	12.7	8.2-18.1
"	-	8.8 (P)	0-14.3 (P)
Uric acid	15.	1.5	0.5-15
"	-	4.8 (P)	1.5-8.7 (P)
Misc. organic compounds			
Cholesterol	-	7.5	3-15
Citric acid	-	1.05 (P)	0-1.92
"	-	-	0.20-3.15 (P)
Glucose	-	19.6	11.28-28.08
"	-	20.7 (P)	14.04-30.00 (P)
Lactic acid	-	1.53	1.53-10
Vitamins			
B ₁ (thiamine)	-	.0007	-
"	-	-	.0002-.0014 (P)
B ₂ (riboflavin)	-	.0050	-
B ₆ (pyridoxine)	-	.0006 (P)	.0001-.0017 (P)
B ₁₂ (cyanocobalamine)	-	.00033 (P)	.00014-.0005 (P)
B _c (folic acid)	-	.0024 (P)	.0003-.0075 (P)
Choline	-	0.65	0.47-0.99
"	-	1.62	0.62-3.64
Niacin (cicotinic acid)	-	.0115 (P)	.00234-.04090 (P)
Pantothenic acid	-	.0088 (P)	.0012-.0190 (P)
C (ascorbic acid)	0.218	.007 (P)	0.058-0.378
"	-	-	0-0.372 (P)
H (biotin)	-	.0008	-
K	-	.0015	-
Enzymes			
Ptyalin	-	-	0-300
Cholinesterase	-	0.33 (P)	0.23-0.43 units/liter ⁴ (P)
Esterase, total	-	0.34 (P)	0.12-0.65 units/liter ⁵ (P)
B-Glucuronidase	-	-	170-1750 units/liter ⁶ (P)
Lipase	-	1.42 (P)	0.25-2.58 units/liter ⁷ (P)
Lipozyme	-	670. (P)	250-1360 units/liter
Phosphatase, acid	-	4.23 (P)	2.5-7.7 units/liter ⁸

* (P) Paraffin stimulated saliva.

Table 13-9
Generation of Hair

a. Growth Rate of Hair

<u>Type</u>	<u>Growth Rate</u>	
	<u>mg/day</u>	<u>mm/day</u>
Facial hair; male Caucasian.	150-200	
Facial hair; adult Caucasian males; age 30-60; electric shaver without preparatory shaving lotion. Mean: 72.3 mg/day	52.1-96.2	
Facial hair; adult Caucasian males; ages 30-60; electric shavers with preparatory pre-shave lotions. Mean: 114.6 mg/day	50.2-153.8	
Facial hair; adult Caucasian males; ages 30-40.	35-40	
Facial hair.	300	
Scalp hair; adult men.		0.305
Hair above ear; adult men.		0.331
Axillary hair; adult men.		0.356
Thigh hair; adult men.		0.153
Chin hair (during summer); adult men.		0.535
Chest hair; adult men.		0.280
Pubic hair; adult men.		0.076
Scalp hair.		0.30-0.5
Head hair.		0.385
Arm hair.		0.214
Facial hair.		0.300-0.500
Scalp hair; 28-yr-old man.	31.6	
Facial hair; 28-yr-old man.	26.9	
Body hair; 28-yr-old man.	22.8	

(After Roth⁽¹⁶⁵⁾ from the data of Cohen⁽³⁴⁾, Mattoni and Sullivan⁽¹²⁵⁾, Spector⁽¹⁹⁵⁾, and Voit⁽²¹⁵⁾)

Table 13-9 (continued)

b. Composition of Hair

All data recorded as mg/100 gm of dry, fat-free material.

	Mean Values		Range	
	Altman and Dittmer, eds. (4)	Spector, ed. (195)	Other	Mattoni and Sullivan (125)
Water	4.2	4.1		
Electrolytes				
Aluminum	2×10^{-6}	3.2		
	-3.6			
Arsenic	0.22	0.22		
Boron	-	-		0.2-0.8
Bromine	-	-		0.2-0.7
Calcium	-	20.8		18-490
Chromium	0.2	0.2		-
Cobalt	1.4-1.8	1.8		1.4-1.8
Copper	-	10.8		0.7-10.8
Iron	-	14.1		0.8-17.0
Lead	-	4.8		1.7-28.4
Magnesium	1.0-10.1	-		-
Manganese	10^{-6} -4.6	3.8		-
Nickel	-	0.8		0.5-0.8
Phosphorus	-	80.0		65-90
Silicon	-	-		15-360
Silver	0.00045	-		-
Strontium	-	-		0.0000022-0.0091
Sulfur	-	3.8	4.7-5.5	-
Titanium	-	-	(198)	0.00320-0.0064
Uranium	0.0127	-		-
Zinc	-	21.2		0.9-44.4
Organic Compounds				
Pentose	30.0	-		-
Protein	-	91.0		85-91
Sugars	80.0	80.0		-

(After Roth⁽¹⁶⁵⁾)

Table 13-10
Generation and Composition of Nails
(After Roth (165))

a. Generation of Nails					
Type	Growth rate (mm/day)		Growth rate (gms)		Source
	Mean	Range	Mean	Range	
Fingernail; 20 yr tests		0.102-0.132			Bean (13)
Fingernail; age 32	0.123				Bean (13)
Fingernail; age 42	0.111				Bean (13)
Fingernail; age 52	0.105				Bean (13)
Thumbnail; adult	0.095				Spector, ed. (195)
Toenail; adult	0.023				Spector, ed. (195)
Fingernail	0.142		0.010 gm/day		Mattoni and Sullivan (125)
Thumbnail	0.130				Mattoni and Sullivan (125)
Toenail	0.036				Mattoni and Sullivan (125)
Fingernail; 81 healthy young adults; both sexes		0.063-0.146			Sibinga (215)
Fingernails and toenails; several individuals over a period of many years			2.02 gms/year		Voit, Part (215)

b. Chemical Composition of Nails				
All data recorded as gms/100 gms				
	Spector, ed.	Silver and Chiego	Rothman	Others
Water*	0.07-0.72	7-12	-	
Chromium	0.012	-	-	
Zinc	0.011	-	-	
Fat	-	0.76-1.15	-	
Keratin components				
Ash	-	0.042	-	
Carbon	-	48.7	-	
Hydrogen	-	6.59	-	
Nitrogen	-	16.55	14.9	
Sulfur	3.3-3.5	3.92	3.8	
Amino acids				
Arginine	-	10.01	8.5	
Cystine	-	2.31	12.0	10.3 (198)
Histidine	-	0.59	0.5	
Lysine	-	3.08	2.6	
Methionine	-	2.47	-	
Phenylalanine	-	-	2.5	
Tryptophane	-	-	1.1	
Tyrosine	-	-	3.0	

* Hygroscopic nature of keratin causes considerable variation in water content.

Table 13-11
Dried Skin and Sebum
(After Roth ⁽¹⁶⁵⁾)

a. Loss of Dried Surface Skin

<u>Subject</u>	<u>Mass</u>		<u>Volume</u>	<u>Source</u>
	lbs/man day	gms/man day	ml/man day	
28-yr-old man	.0013	0.57		Voit, Part III (215) Mattoni and Sullivan (125)
(unspecified)	.0066	3.00	2.8	

b. Generation of Sebum

Sebum is fat excreted from both sebaceous glands and keratinizing cells.

<u>Location</u>	<u>Total Saturation Level*</u>	<u>Casual Level**</u>	<u>Source</u>
Forehead	3.38 mg/cm ²	1.77 mg/cm ²	Rothman (167)
Forehead; hun- dreds of estimates	15.4 mg/40 cm ² (12 hrs)		Rothman (167) after Serrati (185)
Flexor sides of prearm; hundreds of estimates	4.2 mg/40 cm ² (12 hrs)		Rothman (167) after Serrati (185)
Forehead; mean value from reports by 11 investigators	2.82 mg/cm ²		Rothman (167)
Forehead; mean of 234 estimates in men and women ages 16-60 years.	2.89 mg/cm ²		Kirk (103)
Chest, back and shoulder lipids from T-shirt worn by subjects		54 mg/hr	Powe (147)

* Total, or true saturation levels: surface completely protected from accidental removal of fat.

** Casual level: test site not protected against accidental touching, wiping, or contact with clothing (excretions about one-half quantities of true saturation level).

Table 13-12
Composition of Skin Secretions

a.

Major Components of Skin Secretions

	Mean gms/100 gms of excretions	Range
Water	31.7	-
Epithelial cells & protein	61.75	-
Fat	4.16	-
Butyric, Valeric, and Caproic Acid	1.21	-
Ash	1.18	-
Fatty Acids combined	34.6 (Fa)	27.5-41.0 (Fa)
	28.0 (S)	21.0-39.0 (S)
Monoglycerides	3.7	1.8-7.1
Diglycerides	10.1	-
Triglycerides	32.5 (Fa)	14.8-44.0
	44.0 (Fh)	-
	16.0 (S)	16.0-24.8
Waxes (cholesterol esters)	23.7	-
Fatty Acids free	28.3 (Fa)	2.3-38.3
	38.0 (Fh)	-
	33.0 (S)	-
Unsaponifiable matter (total)	30.1 (Fa)	25.1-35.9 (Fa)
	34.0 (S)	29.0-40.0 (S)
Aliphatic alcohols (total)	6.2 (Fa)	4.7-6.9 (Fa)
	9.0 (S)	-
Straight chain	2.4 (Fa)	-
Branched chain	3.8 (Fa)	-
	0.9 (S)	-
Cholesterol	4.1 (Fa)	1.2-9.5
	3.5 (Fh)	-
Dihydrocholesterol	0.1 (Fa)	-
Hydrocarbons	8.1 (Fa)	5.0-20.0
	9.0 (S)	-
Paraffins	1.5	1.2-1.9
Phosphatides	0.9 (Fh)	-
Squalene	5.5 (Fa)	5.5-17.3
	7.0 (S)	-

Fa: forearm

Fh: forehead

S: scalp

(After Roth⁽¹⁶⁵⁾, adapted from Altman and Dittmer⁽⁴⁾, Haahti⁽⁷⁴⁾
and Sunderman and Boerner⁽²⁰¹⁾)

Table 13-12 (continued)

b. Fatty Acids in Human Skin Lipids				
	Free Fatty Acids		Fatty Acids of Waxes & Sterol Esters	
	Mean gms/100 gms of lipid	Range gms of lipid	Mean gms/100 gms of lipid	Range gms of lipid
Tetradecanoic	5.0	3.8-7.7	7.5	3.5-9.3
Tetradecenoic	5.6	4.3-7.8	2.1	1.3-3.6
Pentadecanoic	3.1	2.2-3.7	6.4	4.4-7.8
Pentadecenoic	7.4	5.7-8.5	2.9	1.8-3.4
Branched Hexacecanoic	4.2	2.6-8.6	-	-
Hexadecanoic	10.5	6.8-13.8	33.5	29.2-42.1
Hexadecenoic	41.5	34.2-49.8	33.4	7.5-21.9
Branched Heptadecanoic	6.6	4.8-9.8	4.6	3.5-6.5
Heptadecanoic	1.1	0.6-1.5	2.8	1.5-5.2
Heptadecenoic	3.8	3.3-4.4	3.4	2.9-3.7
Branched Actadecanoic	1.6	1.6-1.7	1.7	1.5-2.0
Actadecanoic	2.1	1.2-3.1	6.5	3.9-13.7
Actadecenoic	7.1	6.3-7.5	12.2	9.8-13.6

c. Major Alcohol of the Waxes and Sterol Esters of Human Skin Surface Lipids

	Mean gms/100 gms of lipid	Range gms of lipid
Tetradecanol	7.7	6.3-9.6
Hexadecanol	8.7	5.9-10.6
Hexadecenol	1.9	1.0-2.9
Octadecanol	12.7	11.3-14.0
Octadecenol	3.8	3.0-4.6
Eicosanol	10.9	9.8-12.6
Eicosenol	19.7	17.6-22.6
Docosanol	4.8	4.2-5.4
Docosenol	7.6	6.2-9.5
Tetracosanol	4.4	3.0-5.8
Tetracosenol	5.3	3.5-5.8
Cholesterol	13.2	11.7-15.6

(After Roth⁽¹⁶⁵⁾, adapted from Haahti⁽⁷⁴⁾)

Table 13-13

Tears and Ear Wax

a.

Generation of Tears

The secretion rate of tears ranges from 0.031 to 0.041 gms/hour, as reported by Sunderman and Boerner⁽²⁰¹⁾ from collections made over a 16-hour period.

b.

Composition of Tears

		<u>Mean Values</u>
		gms/100 ml of tears
Water	98.2%	
Total Solids	1.8	
Ammonia		5.
Ash		1050.
Chlorides (as NaCl)		658.
Nitrogen, total		158.
Nonprotein N		51.
Potassium as K ₂ O		140.
Proteins		669.
Albumin		-
Globulin		-
Sodium as Na ₂ O		600.
Sugar		650.
Urea		30.
Vitamin C		-

(After Roth⁽¹⁶⁵⁾, adapted from Altman and Dittmer⁽⁴⁾, Best and Taylor⁽¹⁵⁾, and Sunderman and Boerner⁽²⁰¹⁾)

c.

Composition of Ear Wax

	<u>Mean</u>	<u>Range</u>
	gms/100	gms of wax
Total lipids	44.	13-64
Phospholipids	0.5	
Non-saponifiable	3.5	
Saponifiable	5.1	
Protein	24.	15-40
Residue	32.	

Also present are 24 or more branched or unbranched fatty acids, and the amino acids alanine, aspartic acid, glutamic acid, glycine, leucine, serine, threonine, tyrosine, and valine.

(After Roth⁽¹⁶⁵⁾, adapted from Akobjanoff et al⁽³⁾, Bauer et al⁽¹²⁾, Chiang et al^(30, 31), and Haahti et al⁽⁷⁴⁾)

Table 13-14
Summation of Human Effluents

a. Total Waste Accumulation/Man-Day for Use in Design
of Environmental Control Systems*

SOLIDS	UNCONTAINED		CONTAINED	
	WEIGHT (grams)	VOLUME (ml)	WEIGHT (grams)	VOLUME (ml)
Misc. Cabin Compounds	0.70	0.72		
Food Spillage (including vomitus)	0.70	0.70		
Desquamated Epithelium	3.00	2.80		
Hair - Depilation loss	0.03	0.03		
Facial Shaving	0.05	0.05	0.25	0.23
Nails			0.01	0.01
Sweat Residue	3.00	3.00		
Sebaceous Residue	4.00	4.00		
Saliva Solids	0.01	0.01		
Mucous Solids	0.40	0.40		
Seminal Residue	0.01	0.01		
Fecal Particles	0.02	0.02		
Micro-organisms	0.16	0.14		
Fecal Solids			20.00	19.00
Urine Solids	<u>0.03</u>	<u>0.02</u>	<u>69.98</u>	<u>65.98</u>
TOTALS	12.11	11.88	89.98	85.98
<u>LIQUIDS</u>				
Fecal Water			100	100
Urine Water			<u>1330</u>	<u>1330</u>
TOTALS			1430	1430
<u>GASES</u>				
Flatus		2,000 ml		
Insensible Water		<u>1,200 ml</u>		
TOTALS		3,200 ml		

* See also Figure 14-14b for wastes during consumption of prototype Apollo diets.

(After General Dynamics⁽⁶⁷⁾)

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
acetaldehyde	D, F, O, U	adenine	D, U	aniline	D
acetamide	D	alanine	D, F, O, U	arabinose	D, O
acetic acid	D, O	aldolase	O	arachidic acid	D
acetic anhydride	D	aldosterone	U	arginine	D, F, O, U
acetoacetic acid	F, O, U	alkaline phosphatase	O	arsenic	F, O, U
acetone	D, F, O, U	allantoin	U	ascorbic acid	O, U
acetonitrile	D, O	allyl alcohol	D	aspartic acid	D, F, O, U
acetophenone	D	aluminum	D, F, U	barium	O
acetylchloride	D	aminobenzoic acid	D, F, U	benzalacetone	D
acetylacetone	D, C	aminobutyric acid	D, F	benzene	D
acetylene	D	aminoisobutyric acid	D, F	benzoic acid	D, F, U
acetylcholine	D, O	aminophenol	D	benzyl alcohol	D, F, U
acetylglucosamine	O	ammonia	D, F, O, U	benzylamine	D
acetylnitrate	D	ammonium sulfate	O, U	benzyl chloride	D, F
acetylurea	D, U	amyl acetate	D	bilifuscin	F
acid phosphatase	O, U	amyl alcohol	D	bilirubin	D, F, U
acrolein	D	amylase	F, O, U	biliverdin	F
acrylic acid	D	androsterone	U	biotin	F, O, U

*
O - oral
D - dermal
F - fecal
U - urinary

(After Weber (220))

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources (continued)

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
boron	F, O	carbonic anhydrase	O	cobalt	F, O
bromine	D, F, U	carbon monoxide	D, F, O	copper	D, F, O, U
butyl acetate	F	catalase	O	coprostanol	F
butyl formate	D	catechol	D, F, U	creatinine	D, F, O, U
butyraldehyde	D, F, O	chloroacetone	D, F, U	coproporphyrin I and III	F, U
butyric acid	D, F, U	chloroacetic acid	D, U	cyanamide	D, F, U
calcium	D, F, O, U	chlorine	D, F, O, U	cyanic acid	D, U
calcium carbonate	F, O, U	chlorobenzene	D	cyanocobalamin	F, O, U
calcium phosphate	D, F, O, U	chlorocarbonic acid	D	cyclopropane	D
calcium sulfate	D, F	chloroprene	D	cyclohexyl amine	F
capric acid	D, F	cholesterol	D, F, O, U	cysteine	D, U
caprylic acid	D, F	cholecalciferol	F, U	cystine	D, F, U
carbamic acid	D, F, U	cholic acid	D, F	dehydroascorbic acid	D, U
carbaryl chloride	D	choline	D, F, O, U	dehydrobilirubin	D, F
carbon dioxide	D, O, U	cholinesterase	O, U	dehydrocholesterol	D, F, U
carbon disulfide	D, F	chromium	U	deoxycholic acid	D, F
carbonic acid	D, O, U	cinnamic acid	D, F	diacetyl	D, O, U
		citruiline	U	diazomethane	D

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources (continued)

COMPOUND	SOURCE	COMPOUND	SOURCE	COMPOUND	SOURCE
dichloroethylene	D	ethyl butyrate	D, F	etiocholanolone	U
diethyl ketone	D, O	ethyl carbonate	D	fluorine	D, O, U
diketogulonic acid	O, U	ethyl chloride	D, O	folic acid	D, O, U
dimethylamine	D, U	ethylene	D, F	folinic acid	F, U
dimethyl sulfide	D, O	ethylene chlorohydrin	D	formaldehyde	D, F, O, U
diphenylamine	D	ethylene chloride	D, U	formamide	D, O
epicoprostanol	F	ethylene diamine	D, F	formic acid	D, F, U
epiguanine	U	ethylene glycol	D	formic ether	D, U
epinephrine	D, O, U	ethylene oxide	D	formyl chloride	D
estradiol	U	ethyl ether	D, O, U	fructose	O, U
estriol	U	ethyl formate	D, F	fucose	D, O
estrone	U	ethylidene chloride	F	furan	D
ethane	D, O	ethyl iodide	D, F	galactosamine	O
ethane thiolic acid	D, F	ethyl mercaptan	D, F, U	galactose	D, O
ethane sulfonyl chloride	D, U	ethyl nitrate	D, F	gluconic acid	F, O
ethyl acetate	D, F	ethyl nitrite	D	glucosamine	D, F, O
ethyl alcohol	D, F, O, U	ethyl propionate	D	glucose	D, F, O, U
ethylamine	D, O	ethyl propyl ether	D, U	glucuronidase	O
ethyl bromide	D	ethyl sulfide	D, F, U	glutamic acid	D, F, O, U

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources (continued)

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
glutamine	U	hydrogen	D, F, O	isocyanic acid	D, O
glutaric acid	D	hydrogen bromide	D, U	isodecanol	D
glyceraldehyde	D, F, O	hydrogen chloride	D, O, U	isoleucine	D, F, O, U
glycerol	D, F	hydrogen phosphide	F	isophthalic acid	D
glycine	D, F, O, U	hydrogen sulfide	D, F	isoprene	D, O
glycoaldehyde	D, F	hydroquinone	D	isopropyl acetate	D
glycolic acid	F	hydroxybutyric acid	F, U	isopropyl alcohol	D, O, U
glycolic aldehyde	D, F	hydroxyproline	D, O, U	isopropyl amine	D
glyoxal	D	hydroxystearic acid	F	isovaleraldehyde	D
glyoxalic acid	D	hypoxanthine	U	kynurenin	F
guanidine	D, F	iminodiacetic acid	O, U	lactase	F
guanine	D, F, U	indole	D, F	lactic acid	D, F, O, U
guanidinoacetic acid	U	inositol	D, O, U	lauric acid	D, F
heteroxanthine	U	indoxyl potassium sulfate	U	lead	F, U
hippuric acid	U	indoxylsulfuric acid	U	leucine	D, F, O, U
histamine	F, O, U	invertase	O	linoleic acid	F
histidine	D, F, U	iodine	D, O, U	lipase	F, O, U
hyaluronidase	O	iron	D, F, O, U	lithium	F, O
hydrocyanic acid	D, F, O, U	isobutyraldehyde	D	lithocholic acid	D, F

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
lysine	D, F, O, U	methyl chloride	D, U	myristic acid	F, O
lysozyme	O, U	methyl ether	D, O, U	niacin	D, F, O, U
magnesium	D, O, U	methyl ethyl ether	D, O, U	niacinamide	F, U
malic acid	D	methyl ethyl ketone	D, O	nickel	F, O, U
malonic acid	D	methyl formate	F	nitric oxide	D, O
maltase	F, O	methyl iodide	D, F	nitrobenzene	D, F
manganese	D, F, O, U	methyl isocyanate	D, F, U	nitrogen	D, F, O, U
mannose	D, O	methyl isothiocyanate	D, F, U	nitrogen dioxide	D, O
margaric acid	F	methyl mercaptan	D, F, U	nitrogen hydrate	F
mesobilirubin	F	methyl nicotinamide	U	nitrogen monoxide	D, O
mesobiliviolin	F	methyl nitrite	D	nitrogen oxychloride	D, O
methane	D, F, O	methyl propyl ether	D, O, U	nitrogen tetroxide	D
methionine	D, F, O, U	methyl sulfide	D, F, O	nitromethane	D
methionine sulfoxide	F, U	methyl thiocyanate	D, O	nitrophenol	D, F
methyl acetamide	D	methyl urea	D, O, U	nondecyllic acid	F
methyl acetate	D, F	methyl vinyl ether	D	norepinephrine	U
methyl alcohol	D, F, O, U	methylxanthine	U	nuclease	F
methyl amine	D, O	methylene chloride	D, F	oleic acid	F
methyl bromide	L, F	molybdenum	F, U	ornithine	D, O, U
methyl carbonate	D, U	mucinase	O	oxalic acid	D, U

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources (continued)

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
oxamide	D, F	phenylalanine	D, F, O, U	propyl formate	D, F
oxygen	D, F, O, U	phosphorus	D, F, O, U	propyne	D
oxyphenyl propionic acid	F	phosphorus tetroxide	F	purine	D, F, U
palmitic acid	D, F	potassium	D, F, O, U	pyridine	D, F
pantothenic acid	D, F, O, U	potassium carbonate	D, F, O	pyridoxal	D, U
paracresol	F	potassium chloride	D, F, O, U	pyridoxamine	O, U
parahydroxyphenylacetic acid	U	pregnanediol	U	pyridoxic acid	U
parahydroxyphenylpropionic acid	U	pregnanetriol	U	pyridoxine	D, F, O, U
parahydroxyphenylpyruvic acid	U	probiolifuscin	F	pyroncomane	F
paraxanthine	U	proline	D, F, O, U	pyrone	D
paracresolsulfuric acid	U	propentidyopent	F	pyrrole	D, F
pelargonic acid	F	propionaldehyde	D, O	pyruvic acid	D, O, U
penta decanoic acid	F	propionamide	D, F	rennin	F
pepsin	O, U	propionic acid	D, F, U	resorcinol	D, F
phenetole	D	propionyl chloride	D	riboflavin	D, F, O, U
phenol	D, U	propyl acetate	D	ribose	D, O
phenol oxidase	O	propyl alcohol	D, O, U	rubidium	O
phenolphthalein	D, F	propylene	D	sarcosine	D, F, U
phenolsulfuric acid	U	propylene oxide	D	selenium	O, U
phenyl acetate	D	propyl ether	D	serine	D, F, U

Table 13-14 (continued)

b. The Chemical Effluents of Man and Their Sources (continued)

<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>	<u>COMPOUND</u>	<u>SOURCE</u>
silicon	U	sulfuryl chloride	F	trimethylamine	D, O
skatole	D, F	taurine	D, O, U	trypsin	F, U
skatoxysulfuric acid	U	taurocholic acid	F	tryptophan	D, F, O, U
sodium	D, F, O, U	tetrahydrocortisol	U	tyramine	F
sodium carbonate	F, O	tetrahydrocortisone	U	tyrosine	D, F, O, U
sodium chloride	D, F, O, U	tetrahydropyran	D	undecyclic acid	F
sodium phenate	D	theophylline	U	urea	D, O, U
sodium sulfate	D, O	thiamine	D, F, O, U	urease	O
sphingosine	F	thiazole	D	uric acid	D, O, U
squalene	D, F	thionyl chloride	F	urobilin	F, U
stearic acid	D, F	thiophene	D	urobilinogen	F, U
strontium	F, O	thiourea	D, U	valeric acid	D, F
succinic acid	D	threonine	D, F, O, U	valine	D, F, O, U
succinopurine	U	tin	O, U	vinyl alcohol	D
sucrase	F	titanium	O	vinyl chloride	D
sucrose	D, O	toluene	D, F	water	D, F, O, U
sulfur	D, F, U	toluidine	D	xanthine	U
sulfur dioxide	D, U	tridecoic acid	F	xylose	D, O
sulfur trioxide	U	trigonelline	U	zinc	O, U

Table 13-14 (continued)

c. Trace Constituents in Effluents of Man According to Organic or Biochemical Groups

<u>CHEMICAL GROUP</u>	<u>NUMBER OF COMPOUNDS</u>
Acid derivatives (except esters)	21
Alcohols	16
Aldehydes and Ketones	17
Amino acids	22
Aromatics	34
Bile derivatives	14
Carbonic acid derivatives	12
Dicarboxylic acids	8
Elements	32
Enzymes	23
Esters	13
Ethers	9
Halongenated hydrocarbons	12
Heterocyclics	19
Hormones	11
Hydrocarbons	12
Inorganics	31
Monocarboxylic acids	31
Nitrogen derivatives	24
Saccharides	11
Sulfur derivatives	13
Vitamins	<u>15</u>
	Total 400
Total sources: Dermal - 271	
Fecal - 196	
Oral - 149	
Urinary - 183	

Table 13-15

Recommended Limits for Contaminants Already Found and Anticipated
in Space Cabins and Submarines

Toxic Hazard Rating

1. SLIGHT: readily reversible effects
2. MODERATE: not severe enough to cause death or permanent injury
3. HIGH: may cause death or permanent injury after very short exposure to small quantities

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Acetaldehyde		200	General narcotic action on the CNS. Irritating to the eyes. High concentrations cause headache and stupefaction.	(177) -p.384
Acetic Acid		10	Irritating to the eyes and mucous membranes. Penetrates the skin easily and can cause dermatitis and ulcers.	(177) -p.386
Acetone		2000 for 24 hrs. 300 for 90 days	Narcotic in high concentrations	(135, 136)
Acetylene	Systemic 1-2	2500 for 24 hrs. 2500 for 90 days	When mixed with oxygen, in proportions of 40% or more, a narcotic. A simple asphyxiant.	(135, 136)
Acrolein		0.1	Particularly affects the membranes of the eyes and respiratory tract.	(177) -p.397
Acrylic Acid	Acute Local: 3		Irritant by ingestion and inhalation	(177) -p.398
Adipic Acid			Details unknown; toxicity probably slight.	(177) -p.399
Alkyl Nitrate			No physiological information available.	
Alkyl Siloxanes			No specific physiological information available. Generally siloxanes are eye irritants.	
Allyl Alcohol		2	Irritation of skin, eyes and mucous membranes. Systemic poisoning is possible.	(177) -p.404
Alumino Silicates		N	No physiological information available.	
Ammonia		400 for 1 hr. 50 for 24 hrs. 25 for 90 days		(135, 136)

*Unless otherwise specified as provisional limits under normoxic conditions by the NAS-NRC(136) the limits are given as TLV (Earth equivalent), covering exposures for 8 hrs/day, 5 days per week at standard temperatures and pressures.

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Ammonia, Anhydrous		50	Irritating to eyes and mucous membranes of respiratory tract. Irritation of the skin may occur, especially if it is moist.	(177) -p.424
Amyl Alcohol	Local:1 Systemic: 2-3		Vapor may be irritating to the eyes and upper respiratory tract.	(177) -p.438
Benzene		100 for 24 hrs. 1 for 90 days	Exposure to high concentrations (3,000 ppm) may result in acute poisoning; narcotic action on the CNS. A definite cumulative action on bone marrow from 100 ppm exposures.	(135, 136)
Bisphenol A		5	As phenol.	(41)
1-3 Butadiene		1000	Vapors are irritating to eyes and mucous membranes. Inhalation of high concentrations can cause unconsciousness and death. If spilled on skin or clothing, it may cause burns or frostbite.	(177) -p.533
Butane	Systemic: 1-2		Simple asphyxiant. Produces drowsiness.	(177) -p.533
2 Butanone		100 for 60 min. 20 for 90 days 20 for 1000 days	Irritation of mucous membranes	(136)
Butene-1	Systemic: 2		An anesthetic and asphyxiant.	(177) -p.545
CIS-Butene-2			Details unknown. May act as a simple asphyxiant.	(177) -p.535
Trans-Butene-2			Toxicity unknown.	(177) -p.535
(N. -) Butyl Alcohol		100 (TLV) 10 for 90 days 10 for 1000 days	Irritation of the eyes with corneal inflammation, slight headache, slight irritation of the nose and throat and dermatitis of the fingers. Keratitis has also been reported.	(136, 177) -p.538
Butyraldehyde	Local:1-2 Systemic: 2		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.	(177) -p.555
Butyric Acid	Local:1 Systemic: 1		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.	(177) -p.555

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Caprylic Acid			Details unknown. Irritating vapors can cause coughing. Experimental data suggest low toxicity.	(177) -p.572
Carbon Dioxide		25,000 for 1 hr. 10,000 for 24 hrs. 5,000 for 90 days	Inhalation. (See Oxygen-CO ₂ -Energy, No. 10.)	(136)
Carbon Disulfide		20	Narcotic and anesthetic effect in acute poisoning, with death following from respiratory failure. Sensory symptoms precede motor involvement. Liver, kidney and heart may be damaged.	(177) -p.575
Carbon Monoxide		50 200 for 1 hr. 200 for 24 hrs. 5 for 90 days 15 for 1000 days	Effect is predominantly one of asphyxia, due to formation of irreversible carboxyhemoglobin in blood. 1,000 to 2,000 ppm for 1 hr. is dangerous, 4,000 ppm is fatal in less than 1 hr.	(135, 136)
Carbon Tetrachloride		10	Narcotic action. High concentrations produce unconsciousness, followed by death. After effects may include damage to kidneys, liver and lungs. 1,000 to 1,500 ppm for 3 hrs. may cause symptoms.	(177) -p.578
Carbonyl Fluoride		25 for 60 min.	Pulmonary irritation (animals)	
Chlorine		1 1 for 24 hrs. 0.1 for 90 days	Irritating to mucous membranes. If lung tissues are attacked, pulmonary edema may result.	(135, 136)
Chlorobenzene		75	Slight irritant. May cause kidney and liver damage upon prolonged exposure.	(177) -p.602
Chloroform		5 for 90 days 1 for 1000 days	Fatty infiltration of liver at toxicological threshold.	(136)
Chloroprene		25	Asphyxiant. Vapor is a central system depressant. Lowers blood pressure. In animals causes severe degenerative changes in the vital organs, especially kidneys and liver.	(177) -p.613

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Chloropropane			No physiological information available, but should have toxic properties similar to ethyl chloride.	
Cupric Oxide	Local:1 Systemic: 1-2		As the sublimed oxide, copper may be responsible for one form of metal fume fever.	(177) -p.633
Cyanamide	Systemic: 1-2		Causes an increase in respiration and pulse rate, lowered blood pressure and dizziness. There may be a flushed appearance of the face. Does not contain free cyanide.	(177) -p.648
Cyclohexane		300	May act as a simple asphyxiant.	(177) -p.652
Cyclohexanol		50	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation, skin absorption.	(177) -p.652
Dichloromethane		25 for 90 days 5 for 1000 days	Reduction of voluntary activity at threshold (in animals).	(136)
2, 2 Dimethylbutane			Toxicity: details unknown.	(177) -p.738
1, 1 Dimethylcyclohexane			No physiological information available.	
Trans -1, 2 Dimethylcyclohexane			No physiological information available.	
Dimethyl Hydrazine		0.5	Can be absorbed through intact skin. May result in convulsive seizures, pulmonary edema and hemorrhage.	(177) -p.746
Dimethyl Sulphide			Toxicity: details unknown. Probably highly toxic.	(177) -p.1007
1-4 Dioxane		100 10 for 90 days 2 for 1000 days	Repeated exposure has resulted in human fatalities, the affected organs being the liver and kidneys. Death results from acute hemorrhagic nephritis. Brains and lungs show edema.	(177,136) -p.760
Epichlorohydrin		5	In acute poisoning, death is the result of respiratory paralysis. Chronic poisoning is the result of kidney damage.	(177) -p.784

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Ethyl Acetate		400 40 for 90 days 40 for 1000 days	Irritating to mucous surfaces. Prolonged or repeated exposures cause conjunctival irritation and corneal clouding. High concentrations are narcotic and can cause congestion of the liver and kidneys.	(177, 136) -p. 789
Ethyl Alcohol		500 for 24 hrs. 100 for 90 days	No cumulative effect. Irritating to eyes and mucous membranes of upper respiratory tract. Narcotic properties.	(135, 136)
Trans-1, ME-3 Ethylcyclohexane			No physiological information available.	
Ethylene	Acute Systemic: 2		High concentrations cause anesthesia. A simple asphyxiant.	(177) -p. 800
Ethylene Dichloride		50	Irritating to eyes and upper respiratory passages. Vapor causes a clouding of the cornea which may progress to endothelial necrosis. Strong narcotic action. Edema of the lungs in animals.	(177) -p. 803
Ethylene Glycol	Local:0-1 Systemic:	0.2 100 for 60 min.	If ingested, it causes initial central nervous system stimulation, followed by depression. Later, it causes kidney damage which may terminate fatally.	(136, 177) -p. 804
Ethyl Sulfide			Details unknown, but probably moderately toxic.	(177) -p. 823
Fluoro Ethylenes			No specific physiological information available. Generally fluorinated compounds are potentially toxic because they yield fluorine, hydrofluoric acid, etc. after ingestion, which are toxic.	
Formaldehyde		5 0.1 for 90 days 0.1 for 1000 days	Toxic effects are mainly irritation. If swallowed it causes violent vomiting and diarrhea which can lead to collapse, increased airway resistance (animals) at threshold.	(136, 177) -p. 844
Fluorotrichloromethane R-11		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days		(135, 136)

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Dichlorodifluoromethane		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days		(135, 136)
F ₂ C1C-C ClF ₂ R-114		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days		(135, 136)
Freons		1000	High concentrations cause narcosis and anesthesia.	(177) -p.843
Hexachlorophene	Local:1		Strong concentrations may be irritating.	(177) -p.993
Hexamethylcyclotrisiloxane			No physiological information available. Generally siloxanes cause eye irritation.	
Hexamethylene Diamine	Acute Local:2		Local: irritant; ingestion, inhalation-all present.	(177) -p.874
N-Hexane		500	Local: irritant; ingestion, inhalation. Systemic: inhalation, ingestion.	(177) -p.875
Hexene-1	Acute Local:2 Acute Systemic: 2		Local: irritant; ingestion, inhalation. Systemic: inhalation	(177) -p.877
Hydrocyanic Acid		10	Can be absorbed via intact skin. A true protoplasmic poison, combining in the tissues with the enzymes associated with cellular oxidation and rendering the oxygen unavailable to the tissues.	(177) -p.883
Hydrogen	Acute Systemic:1	3,000 for 24 hrs. 3,000 for 90 days	Inhalation	(135, 136)
Hydrogen Chloride		10 for 1 hr. 4 for 24 hrs. 1 for 90 days	Irritating to the mucous membranes	(135, 136)
Hydrogen Fluoride		8 for 1 hr. 1 for 24 hrs. 0.1 for 90 days	Inhalation may cause ulcers of the upper respiratory tract. Produces severe skin burns, slow in healing.	(135, 136)
Hydrogen Sulfide		50 for 1 hr.	An irritant and an asphyxiant. The effect on the nervous system is one of depression with small amounts, stimulation with larger ones. Asphyxia is due to paralysis of the respiratory system.	(135, 136)

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Indole			No physiological information available. May be considered an emetic after long exposure.	
Isobutyl Alcohol	Acute Local:3 Acute Systemic: 2	100	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation.	(177) -p.908
Isobutylene			Toxicity: details unknown. May have asphyxiant or narcotizing action.	(177) -p.909
Isoprene	Acute Local:2 Acute Systemic: 2		Concentrations of 5% are fatal.	(177) -p.913
Isopropyl Alcohol		400	Can cause corneal burns and eye damage. Acts as a local irritant and in high concentrations as a narcotic.	(177) -p.914
Lithium Hydroxide	Local:1 Systemic: 1-2		Large doses of lithium compounds have caused dizziness and prostration, particularly on a low sodium intake.	(177) -p.943
Maleic Acid	Acute Local:2		Irritant, ingestion, inhalation.	(177) -p.954
Manganese Oxide	Systemic: 2-3	5 mg per cubic meter of air	The central nervous system is the chief site of damage, usually after 1 to 3 years of exposure to heavy concentrations of dust or fumes.	(177) -p.956
Mercaptans	Acute Local:3 Systemic: 2-3	0.5	Local: irritant; inhalation Systemic: inhalation.	(177) -p.962
Mercury		0.1 mg per cubic meter of air	Chronic low grade exposure affects CNS and kidneys; may sensitize to oxygen toxicity and radiation.	(177) -p.971
Methane	Systemic: 1	5,000 for 24 hrs. 5,000 for 90 days	Inhalation	(135, 136)
Methyl Acrylate		10	Chronic exposure has produced injury to lungs, liver and kidneys in experimental animals.	(177) -p.980

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Methyl Alcohol		200 for 24 hrs. 10 for 90 days	Distinct narcotic properties. Slight irritant to the mucous membranes. Main toxic effect is on the nervous system, particularly the optic nerves. Once absorbed, it is only very slowly eliminated; coma may last 2-4 days. A cumulative poison.	(135, 136)
2-Methylbutanone		20 for 90 days 20 for 1000 days	Irritation of mucous membranes in man at threshold.	(136)
Methyl Chloride		100	Repeated exposure to low concentrations causes damage to the CNS, and less frequently to the liver, kidneys, bone marrow and cardiovascular system. Exposure to high concentrations may result in delirium, coma and death.	(177) -p. 987
Methyl Chloroform		1,000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Local: irritant by ingestion, inhalation Systemic: toxic by ingestion, inhalation	(135, 136)
Methylene Chloride		500	Very dangerous to the eyes. Strong narcotic powers.	(177) -p. 993
Methylethyl Ketone		200	Local irritation and narcosis.	(177) -p. 534
Methyl Isopropyl Ketone		200	No physiological information available. In general it should have same irritant properties as low molecular weight ketones; i.e., eye, skin and respiratory tract irritant.	
Methyl Methacrylate	Acute Local:1 Systemic: 1		Local: irritant by ingestion, inhalation. Systemic: toxic by ingestion, inhalation.	(177) -p. 1000
Methyl Nitrate	Systemic:2		Ingestion, inhalation	(41)
3-Methyl-Pentane			Details unknown; may have narcotic or anesthetic properties.	(177) -p. 1002
Methyl Salicylate	Local:1-2 Acute Systemic:3		Acute accident poisoning is not uncommon. Kidney irritation, vomiting and convulsions occur.	(177) -p. 1005

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Monoethanolamine		50 for 1 hr. 3 for 24 hrs. 0.5 for 90 days	A skin irritant and necrotizer; a central nervous system stimulant in low doses; a depressant at high doses.	(135, 136)
Monomethylhydrazine		0.2	A respiratory irritant and convulsant at low doses.	(136, 223, 224)
Nitric Oxide		5	60-150-ppm-immediate irritation of throat and nose. Shortness of breath, restless, loss of consciousness and death may follow. 100-150 ppm for 30-60 minutes is dangerous.	(177)
Nitrogen Dioxide		10 for 1 hr. 1 for 24 hrs. 0.5 for 90 days	Highly toxic.	(135, 136)
Nitrous Oxide	Acute Systemic: 2		Inhalation	(177) -p.1052
Olefins			Prolonged exposure to high concentrations has led to liver damage and hyperplasia of the marrow in animals; no corresponding effects have been found in humans. Relatively innocuous.	(177) -p.1060
Ozone		1.0 for 1 hr. 0.1 for 24 hrs. 0.02 for 90 days	Strong irritant action on the upper respiratory system.	(135, 136)
N-Pentane	Acute Systemic: 1		Inhalation. Narcotic in high concentrations.	(177) -p.1074
Phenol		5	Can be absorbed through intact skin. Main effect is on the CNS in acute poisoning. Death may result within 30 minutes to several hours of spilling on the skin.	(177) -p.1083
Phosgene		1.0 for 1 hr. 0.1 for 24 hrs. 0.05 for 90 days	Irritating to eyes and throat. The main fatal effect is pulmonary edema.	(135, 136)
Potassium Dichromate		0.1	A corrosive action on the skin and mucous membranes. Characteristic lesion is a deep ulcer, slow in healing. Chromate salts have been associated with cancer of the lungs.	(177) -p.1118

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
Propane	Acute Systemic: 1	1000	Inhalation	(177) -p.1134
N-Propylacetate		200	Causes narcosis and is somewhat irritating. Definite evidence of habituation - not likely to cause chronic poisoning.	(177) -p.1137
Propylene	Acute Systemic: 2		Inhalation. A simple asphyxiant.	(177) -p.1139
Silicic Acid			Toxicity slight, but dangerous in weightless conditions as it may form powders if not well confined.	(177) -p.1171
Skatole			No specific physiological information available. May be considered an emetic after lengthy exposures.	
Sulfur Dioxide		10 for 1 hr. 5.0 for 24 hrs. 1.0 for 90 days	Irritating to nose and throat. <u>MAC</u> for 30-60 minutes exposure is 50-100 ppm. 400-500 ppm immediately dangerous to life.	(135, 136)
Terephthalic Acid			No specific physiological information available. A mild irritant with low acute oral toxicity.	(177)
Tetrachloroethylene		100	Toxic by inhalation, prolonged or repeated contact with the skin, or mucous membranes or when ingested. Liquid can cause injuries to the eyes, irritation of the nose and throat.	(177) -p.1077
Tetrafluoroethylene Inhibited			Toxicity; can act as an asphyxiant and may have other toxic properties.	(177) -p.1230
Toluene		100 for 24 hrs.	Impairment of coordination and reaction time. Few cases of acute toluene poisoning.	(135, 136)
Toluene 2,4 di-isocyanate		0.02	Severe dermatitis and bronchial spasm. Particularly irritating to the eyes.	(136) -p.1259
Tri-aryl phosphates		5.0	As cresol. Ingestion, inhalation skin absorption.	(41)

Table 13-15 (continued)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M ³	Comments	References
1, 1, 1-Trichloroethane		1, 000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Narcotic at low levels. High levels may affect liver and lungs.	(135, 136)
Trichloroethylene		100 10 for 90 days 2 for 1000 days	Inhalation of high concentrations causes narcosis and anesthesia. A form of addiction has been observed. Death from cardiac failure due to ventricular fibrillation has been reported.	(135, 177) -p.1269
1, 1, 2-Trichloro, 1, 2, 2-Trifluoroethane (Freon 113) and congeners		30, 000 for 60 min. 1, 000 for 90 days 200 for 1000 days	CNS and cardiovascular effects at threshold in animals.	(136)
1, 1, 3-Trimethylcyclohexane			No physiological information available. Suspect it should be a skin irritant (solvent action) and irritant of the respiratory tract.	
Urea			Toxicity: no importance as an industrial hazard. Slightly dangerous when heated.	(177) -p.1314
Valeric Acid			Toxicity: details unknown. Nauseating. See Butyric Acid.	(177) -p.1315
Vinyl Acetate	Local:1 Acute Systemic: 1		Local: Irritant Systemic: Inhalation.	(177) -p.1319
Vinyl Chloride		500	In high concentrations it acts as an anesthetic. Causes skin burns by rapid evaporation and consequent freezing.	(177) -p.1321
Vinylidene Chloride		5 for 30 to 90 days	Details unknown. See Vinyl Chloride.	(136)
Xylene		100 for 24 hrs.	Local: irritant. Systemic: inhalation, skin absorption.	(136)

recommended limit is the TLV (Earth equivalent) which covers exposures for 8 hrs./day, 5 days per week at standard temperatures and pressures. Some of the provisional limits for other exposure periods are those recommended by the NAS/NRC. The rationale behind these provisional limits for specific compounds is presented in detail in Reference (136) and general philosophy behind the approach is discussed on pages 13-1 through 13-4.

In brief, the provisional long-term limits recommended were chosen with the objective of avoiding: adverse health effects, either immediate or delayed; degradation of performance; and interference with physiological studies on crew members. The provisional 60-minute emergency limits are designed to avoid significant degradation in crew performance in emergencies and to avoid permanent health injury. They contain essentially no safety factor, and transitory effects may result. Because of the inadequacies of the data mentioned above, particularly the fact that most current toxicologic data are based on non-continuous exposure, and because of uncertainty as to synergism among chemicals, and to allow for the possibility of minor excursions above the ceiling limit, a safety factor has been applied to each 90 and 1000-day limit value. The magnitude of the safety factor differs according to the toxicologic category of the contaminant. If the contaminant is an irritant at the threshold of response, an estimated factor of 5 is included in the limit. If the contaminant is capable of producing systemic, irreversible injury, a factor of 20 is included.

The duration of exposure to which a limit value applies is determined by the type of response induced by a given contaminant. If a local irritant (e.g., the butanones), the Committee felt that so long as the concentration was kept below the irritant level no cumulative effects would occur. In such cases, the 90-day limit applies equally to a 1000-day mission. When, however, the contaminant has the potential for cumulative action, albeit at an exposure level well above the provisional limit for 90 days, a reduction appropriate to the seriousness of the response is made for the 1000-day mission. In such instances, a five-fold reduction in the 90-day limit has been arbitrarily made (e.g., chloroform, dioxane). The other non-TLV limits are those previously recommended for nuclear submarine exposures by the NAS-NRC Committee on Toxicology (135) and accepted as valid for space cabins (136). The toxic hazard rating represents a classification by severity as noted in code at top of table.

Table 13-16 presents a summary of the agents found during different tests and of previous attempts to set limits for exposures other than those for TLV. The references for each column are noted in parentheses after the title. These data of Table 13-16 are presented as historical guides. The limits of Table 13-15 are those currently recommended.

Classification of these and other possible toxic contaminants is available (41, 86). The data are organized alphabetically as well as in chemical classes and sites of action. The chemical classification is noted in Table 13-17 (86) and the toxic effects in body systems, noted in Table 13-18. Tables 13-17 and 13-18 represent check lists of compounds already found in sealed environments as well as some that are suspected as future contaminants.

Table 13-16

Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits
(After NAS-NRC(136))

COMPOUND	MOL. WT.	REPORTED OCCURRENCES														ATMOSPHERIC LIMITS												
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM1 (36)	SAM2 (35)	SAM3 (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV's (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous'	Alert	DOUGLAS(42)	
Acetaldehyde	44.05	X	X					X	X	X	X	X	X	X	X	X	X		200	3				50	5	20	200	Abort
Acetic Acid	60.05						X	X	X						X	X	X		10	2				2	4	1	6	10
Acetone	58.08	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		1000	a	85		2000	300	50	20	80	1000
Acetylene	26.04	X	X	X											X		X					2500	2500	2500	25,000			
Allene	40.07							X																				
Allyl Alcohol	58.08							X	X	X									2									
Ammonia	17.03		X				X		X	X	X					X	X		50	30	400	50	25	25	25	100	100	
Amyl Acetate	130.18									X	X								100	a	20			20				53
Amyl Alcohol	88.15																			25				25				50
Acrylonitrile	53.06						X												20						0.4	1.6	20	
Benzene	78.11	X	X	X	X	X	X	X	X	X			X	X	X	X	X		25	a	6	100	1	5				
Benzyl Ether	198.25							X	X																			
1-3 Butadiene	54.09			X															1000	45			b					
n-Butane	58.12	X	X	X	X	X	X	X			X	X	X	X	X									b	5000			
iso-Butane	58.12							X																				
2-Butanone	72.06	X	X						X	X	X	X	X	X					200	70				100	4	16	200	*

* = Listed under two synonyms

b = Submarine Levels

a = USSR Community Levels available

60 mg/m³

Aliphatic Hydrocarbons

10 mg/m³Aromatic Hydrocarbons
(other than benzene)3 mg/m³

Benzene

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES															ATMOSPHERIC LIMITS												
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	See Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)			Continuous	Alert	Abort
1-Butene	56.10	X	X	X		X		X							X		X							b	4000				
2-Butene cistrans	56.10	X	X				X		X								X						b	4000					
Butyl Acetate	150.61								X										150	a 40					50				
iso-Butyl Acetate	150.61																												
n-Butyl Alcohol	74.12	X	X				X		X					X	X	X			100	65					25				
iso-Butyl Alcohol	74.12	X				X		X	X	X						X									25				
sec-Butyl Acrylate	128.17					X																							
n-Butyl Benzene	134.21																X							b					
tert-Butyl Benzene	134.21									X							X							b					
iso-Butylene	56.10								X		X				X		X							b					
Butyraldehyde	72.10								X	X	X														100				
-Butyrolactone	86.09															X													
Butyric Acid	88.10																X								5				
Carbon Dioxide	44.01	X					X	X	X	X	X	X	X	X	X	X	X		5000		25,000	10,000	5000	5000	10,000	12,500	15,000		
Carbon Disulfide	76.14		X	X						X									20						2				
Carbon Monoxide	28.01		X	X						X	X	X							50	17	200	200	25	25	25	100	100		

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																ATMOSPHERIC LIMITS										
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV's (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	Abort	
Carbon Tetrachloride	153.82						X			X	X	X							See Lab II (78)(176)	10	3				2	.5	2	10
Carbonyl Sulfide	60.07												X		X				Submarines (14)						2			
Chlorine	70.91																X		Offgassing (78)(90)(100)	1			1	0.1	.5	0.4	.16	1.0
Chlorobenzene	112.56									X	X	X								75	11							
1-Chlorobutane	92.57						X																					
Chlorofluoro Bromomethane	147.47						X																					
Chlorofluoro ethylene	80.5			X				X																				
Chloroform	119.38			X	X		X	X	X	X	X	X			X					50								
Chloromethane	50.49			X			X	X	X	X	X									100					200	2	8	100
Chloropropane	78.54	X																										
Cyclohexane	84.16	X	X	X	X		X	X	X	X	X	X					X			300					b	200		
Cyclohexene	82.14								X	X	X	X								300					b			
Cyclopentane	70.13			X	X				X	X	X													b				
Cyclopentene	68.11											X												b				
Cyclopropane	42.08																											
Decalin (various isomers)	138.25									X	X	X																

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	See Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	Abort																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES														ATMOSPHERIC LIMITS												
		Mercury (169)(172)	GT - 3 (78)	GT - 4 (78)	GT - 5 (78)	GT - 7 (78)	GT - 10 (78)	GT - 12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	DOUGLAS (42)	
Dimethylcyclopentane	100.13								X	X													b					
1-3, Dimethyl-5 ethylbenzene	134.22															X							b	25				
Dimethyl Furan	96.13								X	X	X																	
Dimethyl Naphthalene	156.22								X	X													b					
2, 4-Dimethyl Pentane	100.21									X													b					
Dimethyl Propane	72.15								X	X													b					
Dimethyl Sulfide	62.14								X	X															5	4	16	20
Dimethyl Thiophene	112.19								X																			
1, 4-Dioxane	88.11	X	X	X	X			X						X					100	3					10			
Dioxene	86.10	X	X	X	X																				10			
Ethane	30.07	X	X	X	X	X	X	X	X	X						X							b					
Ethanethiol	62.13	X	X	X							X								10						2			
2-Ethoxyethanol	90.12															X			200									
2-Ethoxyethyl Acetate	132.16															X			100									
Ethyl Acetate	88.10	X	X	X			X		X	X	X			X	X	X	X		400	a 55					50			
Ethyl Acetylene	54.09		X																									

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																ATMOSPHERIC LIMITS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	Abort																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS									
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	Abort	
		X	X	X																								
R-22, Chlorodifluoromethane	86.50	X	X	X							X	X													500			
R-23, Trifluoromethane	70.01	X	X																						500			
R-113, FCl ₂ C-CClF ₂	187.39						X				X	X								1000					500			
R-114, F ₂ ClC-CClF ₂	170.93	X	X								X	X	X			X				1000		30,000	20,000	1000	500			
* R-125, F ₂ HC-CF ₃	121.03	X	X								X	X													500			
Furan	68.07				X						X	X	X												10			
Furfural	96.08											X								5								
Furfuryl Alcohol	98.10											X								50								
n- Heptane	100.20						X				X	X	X			X	X	X	500					b	200			
Heptene	98.18										X													b				
Hexafluorobenzene	186.00											X																
Hexamethyl cyclotrisiloxane	166.00	X																							50			
n-Hexane	86.17	X	X	X			X	X	X	X		X	X			X	X	X	500					b	200			
Hexene	84.16	X										X												b				
Hexene-1	84.16	X																						b	1			
Hydrogen	1.01	X	X									X				X							3000	3000	3000	30,000		

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES															ATMOSPHERIC LIMITS												
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	DOUGLAS (42)		
Hydrogen Chloride	36.46																	X		5		10	4	1	0.1	0.1	0.4	5	Abort
Hydrogen Fluoride	20.01											X						X		3		8	1	0.1	0.1	0.1	0.4	3	
Hydrogen Sulfide	34.08		X								X	X	X					X		10	7 ^a	50			2	4	16	20	
Indene	116.15						X				X																		
Indole	117.14										X														0.5				
Isoprene	68.11						X			X	X	X			X										200				
Isopentane	72.15	X	X							X	X	X	X				X							b	1,000				
* Mesitylene	120.19									X	X						X							b					
Methane	16.04	X	X	X	X	X	X	X	X	X	X	X			X		X	X					5,000	5,000	2,500				
Methyl Acetate	74.08									X	X	X								200	35				25				
Methyl Alcohol	32.04	X	X	X	X	X	X	X	X	X	X	X	X	X		X			200	40		200			10	3	4	16	200
Methylamine	31.06									X									10						1				
2-Methylbutanone-3	86.13	X									X																		
Methyl Chloride	50.49		X				X	X				X							100						200	2	8	100	
Methyl Chloroform	133.42	X								X	X	X			X				350		1000	500	200	50					
Methyl Cyclohexene	96.17										X													b					

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES														ATMOSPHERIC LIMITS												
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	DOUGLAS (42)	
			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										X
Methyl Cyclopentane	84.13									X					X			X					b					
* Methylene Chloride	84.89	X	X	X	X	X	X	X	X	X	X	X	X	X	X					500	14				100			
Methyl Cyclohexane																		X	X	500				b				
Methylethyl benzene	120.19														X								b	20				
Methyl Ethyl Ketone	72.06	X	X				X	X	X	X	X	X	X	X	X	X	X			200	70				100	4	16	200
Methyl Ethyl Thiophene	126.18									X																		
Methyl Formate	60.05											X							100						10			
Methyl Furan	82.10									X	X	X													10			
Methyl iso Butyl Ketone	100.16									X	X	X			X	X			100						10			
Methyl iso Propyl Ketone	86.13	X										X		X														
Methanethiol	48.10								X		X	X							10						2	1	4	50
Methyl Methacrylate	100.11														X				100						10			
Methyl Naphthalene	142.19									X	X													b				
Methyl Butyrate	102.13									X	X	X																
2-Methyl Pentane	86.17	X									X	X												b				
3-Methyl Pentane	86.17	X	X																					b	1000			

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS									
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)	ACGIH TLV'S (6)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	DOUGLAS (42)	
4-Methyl-2 Pentanone	100.16						X																					
Methylsiloxane Polymers								X	X	X						X												
Methyl Thiophene	84.14						X		X																			
Monochloro Acetylene	60.48										X																	
Monoethanolamine	75.11									X							X			3		50	3	0.5	1			
Napthalene	128.16								X	X	X								10									
Nitric Oxide	30.01								X							X									1	0.4	1.6	10
Nitrogen Dioxide	92.01											X				X			5		10	1	0.5	.5	0.2	0.8	5	
Nitrous Oxide	44.01															X								5000				
n-Nonane	128.25																X							b				
Octane	114.23										X					X			500					b				
* iso-Octane	114.23		X					X	X									200						b				
Ozone	48.00															X			0.1		1.0	0.1	0.02	0.05	0.004	0.016	0.1	
Pentafluoroethane	121.03	X	X					X																	500			
Pentane	72.15	X	X					X	X	X	X						X		1,000					b	1,000			
iso-Pentane	72.15	X	X					X	X	X	X						X							b	1,000			

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES														ATMOSPHERIC LIMITS														
																SUBMARINE (135)				Boeing Company (86)		DOUGLAS (42)								
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	Sea Lab II (78)(176)												
1-Pentene	70.13							X			X																			
Perchloroethylene	165.85		X						X	X	X				X						100									
Phenol	94.11																				5	1.3								
Phosgene	98.92																				0.1						0.05	0.04	0.16	1.0
Propane	44.09	X	X	X	X	X	X	X	X	X	X							X		1,000				b	1000				1800	
Propene	42.08					X																								
Propenenitrile	53.06						X														20							0.4	1.6	20
Propionaldehyde	58.08															X									50					
Propionic Acid	74.08								X	X					X		X								2					
Propyl Acetate	102.13								X	X	X									200	50									
n-Propyl Alcohol	60.09	X	X						X	X	X			X		X				200	80					100				
iso-Propyl Alcohol	60.09		X	X	X	X	X		X	X	X				X	X				400	80					100				
iso-Propyl Benzene	120.19																			50						20				
n-Propyl Benzene	120.19										X						X													
*																														
Propyl Chloride	78.54	X																												
Propylene	42.08	X	X								X	X	X	X		X				X										

Table 13-16 (continued)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
		Mercury (169)(172)	GT-3 (78)	GT-4 (78)	GT-5 (78)	GT-7 (78)	GT-10 (78)	GT-12 (78)	SAM I (36)	SAM II (35)	SAM III (1)	Mesa I (40)(175)	Mesa II (40)	Merc. Malfunction (169)	Integrated L/S/S (87)(208)	Offgassing (78)(90)(100)	Submarines (14)	See Lab II (78)(176)	USSR Industrial (213)	1 Hour	24 Hour	90 Day	Boeing Company (86)	Continuous	Alert	Abort																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							

Table 13-16 (continued)

[illegible]

Table 13-17
Chemical Classification of Contaminants Already Found or Predicted in Space Cabins
(After Hine and Weir⁽⁸⁶⁾)

ACIDS, INORGANIC (2)

Hydrogen fluoride
Sulfuric acid

ACIDS, ORGANIC (8)

Acetic acid
Butyric acid
Formic acid
Hippuric acid
Lactic acid
Oxalic acid
Propionic acid
Pyruvic acid

ALCOHOLS (11)

Allantoin
iso-Amyl alcohol
Benzyl alcohol
n-Butyl alcohol
iso-Butyl alcohol
sec.-Butyl alcohol
tert.-Butyl alcohol
Ethanol
Methanol
n-Propyl alcohol
iso-Propyl alcohol

ALDEHYDES (7)

Acetaldehyde
Acrolein (unsaturated
aliphatic ald.)
n-Butyraldehyde
Formaldehyde
Propionaldehyde
n-Valeraldehyde
iso-Valeraldehyde

ALIPHIC HYDROCARBONS (9)

n-Butane
Dimethylbutane
n-Heptane
n-Hexane
Methane
3-Methylpentane
n-Pentane
iso-Pentane
Propane

AMIDES (2)

Formamide
Urea

AMINES (7)

Dimethylamine
Ethylamine
Ethylamine diamine
Histamine
Methylamine
Monoethanolamine
Trimethylamine

AROMATIC HYDROCARBONS (13)

Benzene
Cumene
1, 3-Dimethyl-5-Ethylbenzene
Ethylbenzene
p-Ethyl toluene
Pseudocumene
Resorcinol
Toluene
Cyclohexane
1, 3, 5, -Trimethylbenzene
m-Xylene
o-Xylene
p-Xylene

ESTERS (8)

n-Amyl acetate
n-Butyl acetate
Ethyl acetate
Ethyl formate
Methyl acetate
Methyl formate
Methyl methacrylate
Triaryl phosphate

ETHERS (5)

1, 4-Dioxane
Ethyl ether
Furan
Methyl furan
Tetrahydrofuran

GLYCOLS (1)

Ethylene glycol

HALOGENATED HYDROCARBONS (16)

Carbon tetrachloride
Ethylene dichloride
Freon-11
Freon-12
Freon-22
Freon-23
Freon-113
Freon-114 sym
Freon-114 uns
Freon-125
Methyl bromide
Methyl chloride
Methyl chloroform
Trichloroethylene
Vinyl chloride
Vinylidene chloride

HYDRAZINES (3)

Hydrazine
uns-Dimethyl hydrazine
Monomethyl hydrazine

Table 13-17 (continued)

INDOLES (4)

Indican
Indole
Skatole
Skatoxyl Sulfuric acid

INORGANIC GASES (7)

Chlorine
Hydrogen
Hydrogen chloride
Nitrogen
Oxygen
Ozone
Radon

INORGANIC HYDRIDES (7)

Ammonia
Arsine
Decaborane
Pentaborane-9
Phosphene
Stibine
Water and Water Vapor

KETONES (5)

Acetone
Chloroacetone
Cyclopentanone
Methyl ethyl ketone
Methyl isobutyl ketone

METALS AND THEIR OXIDES (22)

Aluminum
Antimony
Beryllium
Cadmium
Calcium
Chromium
Copper
Gold (metal only)
Iron
Lead
Magnesium
Manganese
Mercury
Molybdenum
Nickel
Potassium
Tellurium
Selenium
Silver
Sodium
Titanium
Zinc

MISCELLANEOUS (2)

Cigarette smoke
Gasoline

NITRILES (3)

Acetonitriles
Hydrogen cyanide
Methyl isocyanide

NITROGENOUS BASES (2)

Creatinine
Uric acid

OXIDES, INORGANIC (4)

Nitric oxide
Nitrogen dioxide
Nitrous oxide
Sulfur dioxide

OXIDES, ORGANIC (6)

Carbon dioxide
Carbon Monoxide
Nitrogen oxychloride
Phosgene
Sulfuryl chloride
Thionyl chloride

PHENOLS (2)

p-Cresol
Phenol

SILICON COMPOUNDS (1)

Hexamethylcyclotrisiloxane

SULFIDES (6)

Carbon disulfide
Carbonyl sulfide
Dimethyl sulfide
Ethyl sulfide
Hydrogen sulfide
Methyl sulfide

SULFUR COMPOUNDS (2)

Ethyl mercaptan
Methyl mercaptan

UNSATURATED ALIPHATIC HYDROCARBONS (9)

Acetylene
Butene-1
cis-Butene-2
trans-Butene-2
Ethylene
Hexene-1
Isoprene
Methyl acetylene
Propylene

Table 13-18

Classification of Possible Contaminants of the Space Capsule According
to Their Toxic Effects on Different Body Systems

(After Hine and Weir⁽⁸⁶⁾)

	Autonomic N.S.	Blood	Cardiovascular	CNS Depressant	CNS Stimulant	Enzyme Inhibitor	Hemopoietic Tissue	Hepato Agent	Mucous Membrane	Nephro Agent	Peripheral N.S.	Respiratory	Simple Asphyxiant
	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Acetaldehyde				*								*	
2. Acetic acid									*			*	
3. Acetone				*					*				
4. Acetonitrile					*	*						*	
5. Acetylene				*					*				*
6. Acrolein									*	*		*	
7. Allantoin													
8. Aluminum												*	
9. Ammonia					*				*			*	
10. iso-Amyl alcohol			*	*					*			*	
11. n-Amyl acetate				*					*			*	
12. Antimony			*					*		*		*	
13. Arsine		*						*	*	*		*	
14. Benzene			*	*			*		*			*	
15. Benzyl alcohol				*									
16. Beryllium						*			*	*		*	
17. n-Butane				*									*
18. Butene-1				*									*
19. cis-Butene-2				*									*

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
20. trans-Butene-2				*									*
21. n-Butyl acetate				*					*			*	
22. n-Butyl alcohol				*				*	*	*		*	
23. iso-Butyl alcohol				*					*			*	
24. sec-Butyl alcohol				*					*			*	
25. tert-Butyl alcohol				*					*				
26. n-Butyraldehyde									*			*	
27. Butyric acid									*				
28. Cadmium										*		*	
29. Calcium									*			*	
30. Carbon dioxide				*									*
31. Carbon disulfide					*	*					*		
32. Carbon monoxide		*											
33. Carbon tetrachloride			*	*				*		*			
34. Carbonyl sulfide					*	*							
35. Chlorine									*			*	
36. Chloroacetone									*			*	
37. Chromium									*	*		*	
38. Cigarette smoke (?)													
39. Copper									*			*	
40. Creatinine				*									
41. p-Cresol					*				*	*		*	
42. Cumene				*				*	*			*	
43. Cyclohexane				*				*		*			
44. Cyclopentanone				*									
45. Decaborane				*									

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
46. Dimethylamine												*	
47. Dimethylbutane				*									
48. 1-3-Dimethyl-5-ethylbenzene													
49. uns-Dimethyl hydrazine(UDMH)					*								
50. Dimethyl sulfide						*							
51. 1,4 Dioxane				*				*	*	*		*	
52. Dioxene				*					*				
53. Ethanol				*					*				
54. Ethyl acetate				*					*			*	
55. Ethylamine			*						*				
56. Ethyl benzene				*					*			*	
57. Ethylene				*									
58. Ethylene diamine								*	*	*		*	
59. Ethylene dichloride				*				*		*		*	
60. Ethylene glycol										*		*	
61. Ethyl ether				*					*				
62. Ethyl formate				*					*			*	
63. Ethyl mercaptan				*									
64. Ethyl sulfide						*			*				
65. p-Ethyl toluene				*					*			*	
66. Formaldehyde									*			*	
67. Formamide									*				
68. Formic acid									*				
69. Freon 11				*					*				*
70. Freon 12				*					*				*

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
71. Freon 22				*					*				*
72. Freon 23				*					*				*
73. Freon 113				*					*				*
74. Freon 114-sym													
75. Freon 114-unsym													
76. Freon 125													
77. Furan				*					*				
78. Gasoline vapors				*					*				
79. Gold								*		*			
80. n-Heptane				*					*				
81. Hexamethylcyclo- trisiloxane									*			*	
82. n-Hexane									*			*	*
83. Hexene-1				*					*				
84. Hippuric acid									*				
85. Histamine	*		*										
86. Hydrazine					*			*		*			
87. Hydrogen													*
88. Hydrogen chloride									*			*	
89. Hydrogen cyanide					*	*							
90. Hydrogen fluoride						*		*	*	*		*	
91. Hydrogen sulfide						*			*			*	
92. Indican									*				
93. Indole		*							*				
94. Iron												*	
95. Isoprene				*					*				
96. Lactic acid									*				

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
97. Lead				*									
98. Magnesium				*					*				
99. Manganese				*				*				*	
100. Mercury			*		*			*		*			
101. Methane				*									*
102. Methanol				*		*					*		
103. Methyl acetate				*								*	
104. Methyl acetylene				*								*	
105. Methyl amine												*	
106. Methyl bromide				*				*				*	
107. Methyl chloride									*			*	
108. Methylene chloride				*					*				
109. Methylchloroform			*	*				*	*				
110. Methyl ethyl ketone				*					*			*	
111. Methyl formate				*					*			*	
112. Methyl furan				*					*			*	
113. Methyl cyanide						*							
114. Methyl isobutyl ketone				*								*	
115. Methyl mercaptan						*						*	
116. Methyl methacrylate				*					*				
117. 3-Methylpentane				*					*				
118. Methyl sulfide												*	
119. Molybdenum									*			*	
120. Monoethanolamine								*	*	*		*	
121. Nickel									*			*	
122. Nitric oxide				*					*			*	

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
123. Nitrogen													*
124. Nitrogen dioxide									*			*	
125. Nitrogen oxy- chloride									*			*	
126. Nitrous oxide				*									*
127. Oxalic acid									*	*			
128. Oxygen						*						*	
129. Ozone						*			*			*	
130. Pentaborane-9					*								
131. n-Pentane				*									
132. iso-Pentane				*									
133. Phenol		*	*					*		*			
134. Phosgene												*	
135. Phosphene								*		*		*	
136. Potassium									*			*	
137. Propane				*									*
138. Propionaldehyde				*					*				
139. Propionic acid									*			*	
140. n-Propyl alcohol				*					*				
141. iso-Propyl alcohol				*					*				
142. Propylene				*									*
143. Pseudocumene				*					*				
144. Pyruvic acid									*			*	
145. Radon		*					*						
146. Resorcinol									*			*	
147. Selenium								*		*			

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
148. Silver												*	
149. Skatole												*	
150. Skatoxylsulfuric acid												*	
151. Sodium									*			*	
152. Stibine		*				*						*	
153. Sulfur dioxide									*			*	
154. Sulfuric acid									*			*	
155. Sulfuryl chloride									*			*	
156. Tellurium						*		*					
157. Tetrahydrofuran				*				*	*	*		*	
158. Thionylchloride									*			*	
159. Titanium		*										*	
160. Toluene				*				*	*	*			
161. Triaryl phosphate											*		
162. Trichloroethylene								*	*	*		*	
163. Trimethylamine									*			*	
164. 1,3,5-Trimethylbenzene				*				*	*				
165. Urea													
166. Uric acid													
167. n-Valeraldehyde									*			*	
168. iso-Valeraldehyde									*			*	
169. Vinyl chloride				*				*					
170. Vinylidene chloride				*					*				
171. Water and water vapor													

Table 13-18 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13
172. m-Xylene								*	*			*	
173. o-Xylene								*	*			*	
174. p-Xylene								*	*			*	
175. Zinc									*				

A more detailed outline of toxic response is given for each compound under "comments" in Table 13-15 or in the references of this table.

The recommendation for "alert levels" and "abort" and TLV_{space} in the classifications of References (42) and (86) must still be looked on with some skepticism because of the complexity of variables covered above. The rationale in Reference (86) is well documented and is a good source for basic data. These data represent the first attempt at the extrapolation for many compounds and should be strictly viewed as such. Papers on Soviet toxic hazard standards are available for comparison of general approaches to industrial values (56, 168, 213).

The reproducibility of the levels of toxic materials found in space cabin simulators has been recorded (36). Detailed analyses of these materials illustrate the variability of data from sample to sample and laboratory to laboratory. At the present state of the analytic and sampling art, any data on "the highest concentration" found in sealed cabins must be viewed with the appropriate level of skepticism suggested by these data.

Malfunctions and Emergencies

In addition to materials present during normal operations, one must consider the toxic atmospheres resulting from fire or equipment failure. Some of these may be subtle and never anticipated (174, 175). (See also page 13-82 .)

Gaseous products from burning of plastics and other materials have been noted as have the toxic products of fire extinguishers and the extinguishing process (80, 101, 162, 164). One must consider not only the products of overt fires but those from thermal decomposition due to overheating of equipment. Toxic atmospheres result from thermal decomposition of electrical equipment, hydraulic fluid, and oil. Low temperature greases volatilize and electrical insulation may char. On occasion, selenium rectifiers have given problems in aircraft. Pyrolyses of hydraulic fluids including the silicones, fluorohydrocarbons, and phosphate esters have given off materials which are irritating to the eye and respiratory tract. Carbon monoxides and aldehydes are frequent breakdown products in equipment failure.

Freon decomposition products form on contact of this class of compounds with hot surfaces. These may include hydrogen halides. The toxicity of pyrolysis products of the freons are now under study (80). Moreover, even unpyrolyzed fire-extinguishing agents are toxic at higher concentrations. A summary of these effects is available (101, 162).

Thermal degradation of plastics will yield monomers (89). Though this occurs generally at high temperatures, the percentage conversion in the case of polytetrafluoroethylene, polymethacrylate, and polymethylstyrene is high. Breakdown of plastics from large chain fragments may also include small molecules not particularly related to the structural unit; thus, methyl alcohol, hydrochloric acid, hydrofluoric acid and hydrogen cyanide may result from the vinyl halide and acrylonitrile polymers; carbonyl fluoride, from tetrafluoroethylene. The arcing of electrical equipment and ionizing radiation may produce photooxidation products of vapors in the atmosphere. Some of the more obvious reactions and products have been recorded (5, 41, 180).

The Bureau of Medicine and Surgery, U. S. Navy, has recommended interim threshold limits for 1-hour exposures to materials that may arise from malfunction of equipment as noted in Table 13-19a. It was emphasized that such limits represent the maximum allowable concentrations permissible under operational conditions and are not to be construed as permissible limits for repeated short-term exposures. It is envisioned that sufficient time between these peak exposures will have elapsed to allow complete recovery of the exposed individuals. In some cases, minor symptomatology may occur.

Table 13-19b gives the 60-minute provisional emergency limits for 5 substances for which no limits are available from the U. S. Navy submarine control program (136). In developing these limits, an attempt was made to follow the principles used by the NAS-NRC Committee on Toxicology

Table 13-19

Maximum Permissible Limits for Exposures Not Exceeding One Hour

a. U.S. Navy Limits

Ammonia	400 ppm
Monoethanolamine	100 ppm
Ozone	1 ppm
Oxides of nitrogen	10 ppm
Carbon dioxide	5%
Carbon monoxide	200 ppm
Hydrogen chloride	50 ppm
Hydrogen fluoride	5 ppm
Phosgene	1 ppm
Sulfur dioxide	10 ppm

(After U.S. Navy (212))

b. Provisional Emergency Limits for Space Cabin Contaminants Under Normoxic Conditions

Air Contaminant	Air Limit in Millimoles per 25 M ³ (ppm) for 60 min
2-Butanone	100
Carbonyl fluoride	25
Ethylene glycol	100
2-Methylbutanone	100
1,1,2-Trichloro, 1,1,2,2-Trifluoroethane and related congeners.	30,000

(After NAS-NRC (136))

in establishing emergency inhalation exposure limits for military and space chemicals (135, 212). Foremost among these principles as applied here is that the exposure not seriously interfere with the performance of a task or result in irreversible injury, although transient effects may be experienced. The emergency limits for these compounds contain no safety factor. They are considered to be tolerable for a single emergency during the duration of the mission. In addition to solvents (the butanones), carbonyl fluoride (COF_2) can provide an acute, short-term hazard from two material sources: pyrolytic decomposition of carboxy nitrosofluoride rubber at and above 450°F , and of polytetrafluoro ethylenes at and above 850°F . Accidental air contamination by ethylene glycol (CH_2OH_2) can arise from leaks in heat-exchange fluid systems or from its projected use as a space-suit coolant. Accidental contamination of the air with 1,1,2-trichloro, 1,2,2-trifluoroethane and its pyrolytic products can occur from its use as a fire extinguisher. These two contaminants, trichloroethylene and 1,1,2-trichloro, 1,2,2-trifluoroethane pose special hazards in the event of subnormal operating temperatures of the catalytic burners. Dichloroacetylene ($\text{ClC} = \text{CCl}$) which is highly hazardous to health at extremely low levels, arises from the thermal degradation of trichloroethylene (174, 175). Similarly, products of high, but lesser toxicity arise from the pyrolysis of 1,1,2-trichloro, 1,2,2-trifluoroethane, and related halogenated freon hydrocarbons (162).

Accidents in the launch and preparation areas as well as on board future spacecraft where extravehicular maneuvering units may be serviced may lead to exposure to rocket fuels and oxidizers. Some of the agents in Tables 13-15 to 13-18 fall into this group of compounds. Since accidental exposure to rocket fuels will probably lead to acute toxicity from relatively large doses of the compounds, data have been obtained for these modes of exposure. Definitive data are lacking for many of the following fuels, especially the interhalogen compounds: (7)

Hydrazine - N_2H_4

1 - 1 dimethylhydrazine - $(\text{CH}_3)_2\text{N}-\text{NH}_2$

Monomethylhydrazine - $\text{CH}_3\text{NH}-\text{NH}_2$

Pentaborane - B_5H_9

Decaborane - $\text{B}_{10}\text{H}_{14}$

Fluorine Containing Compounds:

OF_2	NF_3	TAMA
ClF_3	N_2F_4	TVOPA
ClF_5	NF_3O	NFPA
BrF_5	PFG	Compound R

Beryllium Containing Compounds:

Be
 BeH_2

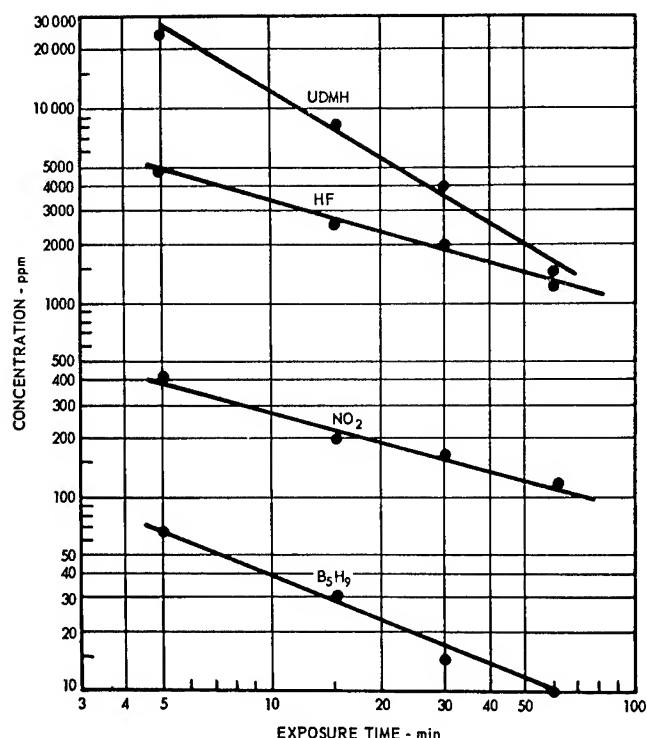
Figure 13-20a represents short-term toxic exposures to several of the more common compounds. These are data obtained on animals. They are presented to show the strong time-dependence of these agents. Table 13-20b shows the recommended TLV (8 hr) and provisional emergency tolerance limits for short times to rocket fuels and oxidizers with comparative data in animals showing wide range of species specificity of tolerance to these agents. Data are being obtained on the handling and toxicity of fluorine and other exotic propellants (7, 183, 227).

Carbon monoxide (CO), among all the spacecraft and launch pad contaminants presently known or envisaged for the immediate future, held a pre-eminent place of concern for the NAS-NRC Committee, primarily because it may well be the limiting toxicant. The following discussion is taken directly from the Committee Report (136). As covered above, carbon monoxide is contributed by materials, by some regenerative systems, and by man himself. CO from materials arise from the oxidative degradation of organics; in regenerative systems, CO is associated with the incomplete reduction of CO_2 . In man, CO is produced from normal degradation of hemoglobin at a rate of about 0.4 ml/hr/man (188, 206). Because of its capacity to interfere with oxygen transport to the tissues and thus to affect cardiovascular and central nervous system function, CO has a broad capacity to synergize or potentiate biologic responses by altering host susceptibility.

The rate of CO uptake depends on its concentration and on the partial pressure of oxygen in the ambient atmosphere; its uptake is dependent on

Figure 13-20

Acute Toxicity of Propellants and Their Products



a. Toxicity of Fuels and Oxidizers in Rats

These data represent a compilation of animal studies covering comparative short-term inhalation toxicities of several fuels and oxidizers: unsymmetrical dimethyl hydrazine (UDMH); hydrofluoric acid (HF); nitrogen dioxide (NO_2); and pentaborane (B_5H_9). The data are presented to show the steep slopes of LC_{50} versus time. The very toxic nature of these compounds makes extrapolation to human LC_{50} 's most difficult.

(After Back and Pinkerton⁽⁸⁾, adapted from Carson et al^(28,29), Weeks et al⁽²²¹⁾, and Weir et al⁽²²²⁾)

Figure 13-20 (continued)

b. Provisional Tolerance for Acute Exposure to Propellants and Toxic Products

Propellant	TLV (8 hr)	Emergency tolerance limits (No irreversible injury in humans)			No death in rats		No pathology in dogs	
		10 min	30 min	60 min	5 min	60 min	5 min	60 min
	ppm		ppm		ppm	ppm	ppm	ppm
Unsymmetrical di-methyl hydrazine (UDMH)	0.5	100	50	30	19,800	813	600	50
Hydrazine (N ₂ H ₄)	1.0	30	20	10	-	-	-	-
Pentaborane (B ₅ H ₉)	0.005	-	-	-	62	7.5	-	-
Nitrogen tetroxide (N ₂ O ₄)	5.0	30	20	10	190	72	104	28
Hydrofluoric acid (HF)	3.0	-	-	-	3,000	900	-	157
Ammonia	-	500	300	300				
Bromine pentafluoride* (Br F ₅)	-	3	1.5	0.5				
Chlorine trifluoride (Cl F ₃)	-	7	3	1				
Chlorine pentafluoride* (Cl F ₅)	-	3	1.5	0.5				
Diborane (B ₂ H ₆)	-	10	5	2				
Ethylene Oxide (C ₂ H ₄ O)	-	650	400	250				
Fluorine (F ₂)	0.1	15	10	5				
Hydrochloric acid (HCl)	5.0	30	20	10				
JP-5 (in mg/L)* ±	-	5	5	2.5				
Monomethyl hydrazine (MMH)	0.2	10	7	3				
Nitrogen dioxide (NO ₂)	5.0	30	20	10				
Nitrogen trifluoride (NF ₃)	10.0	-	-	-				
Nitrogen trioxide (NO ₃)	-	-	100	50				
Oxygen difluoride (OF ₂)	0.05	0.5	0.2	0.1				
Perchloryl Fluorine (ClO ₃ F)	50	20	10					

* More data needed - very tentative levels

± Atmospheric maximum for total hydrocarbons from the fuel approximating saturated values is 5 mg/L.

(After Back⁽⁸⁾, from the data of Carson et al^(28, 29), Weeks et al⁽⁶⁷⁾, Weir et al^(222, 225, 226). Emergency tolerance limits are the recent recommendations of the NAS-NRC⁽¹³⁴⁾)

pulmonary diffusion. For men at work, the equilibrium concentration of carbon monoxide at levels up to 100 ppm reacting with hemoglobin in the blood is substantially complete in 6-8 hours. When the air contains 100 ppm of CO, the blood at equilibrium will contain 18-20% of carbon monoxide hemoglobin (HbCO); at 50 ppm of CO, 8-10% HbCO; at 25-30 ppm CO, 4-5% HbCO (25, 156, 192).

Recent investigations indicate that exposures to very low concentrations of CO can cause a subtle but significant decrement in high-level performance. Symptoms of headache, fatigue, and dizziness appear in healthy workers engaged in light labor when approximately 10% of the hemoglobin is HbCO (attained by breathing air containing 50 ppm of CO for 6-8 hours) (97, 115, 126, 146, 179, 217). The earliest detectable changes occur in the higher centers of the central nervous system. Cognitive and psychomotor abilities decrease at levels of 5% HbCO and the impairment increases with increasing concentration of CO in the blood stream (184). There was a suggestion that levels below 5% HbCO also affected function, but this was not established in the study. Reduction of the threshold of light sensitivity of the eye at 5% HbCO is equivalent in magnitude to that caused by an altitude of 8,000 - 10,000 feet above sea level (77, 123, 184). (See Table 2-57.) These reports of effects at such low levels of HbCO are of particular concern, not so much from the standpoint of their being a serious threat to health, but because they might compromise the high level of judgment and performance that is required of the pilots and other occupants of space vehicles. Subjects may accommodate to the effects of inhaled CO. When men were exposed continuously in a submarine at 50 ppm CO they complained of headache, but a 60-day exposure of 40 ppm was without observed effect (54).

Carbon monoxide has been shown to be synergistic with the toxic action of several other atmospheric contaminants (217). However, those experimental tests were conducted at relatively high concentrations of acute exposure, and there is no information available concerning the threshold concentrations at which significant toxicologic interactions of CO with other contaminants might occur. It is reasonable to assume, however, that during space flight, conditions which would increase an individual's sensitivity to CO might occur (e.g., decreased cardiac output, severe exercise hypoxemia). Further studies are needed to evaluate these factors.

In view of the decrement of CNS and visual function that have recently been reported at HbCO levels of 5% or less, and because there is inadequate information concerning the threshold concentration at which CO might decrease the physiological reserve, the Committee felt that the concentration of CO should be kept as low as possible. Consistent with this philosophy, therefore, the Committee recommended a provisional limit of 15 millimoles/25 m³ (15 ppm) for both 90 and 1000-day missions. At this concentration it is probable that the HbCO level at equilibrium would not exceed 2% or 3%, only slightly greater than the normal level in individuals with no environmental exposure to CO (6).

Figure 13-21 represents the effects of acute exposure to carbon monoxide used to set military limits. Specific effects of carbon monoxide on vision are covered in Light Environment, (No. 2).

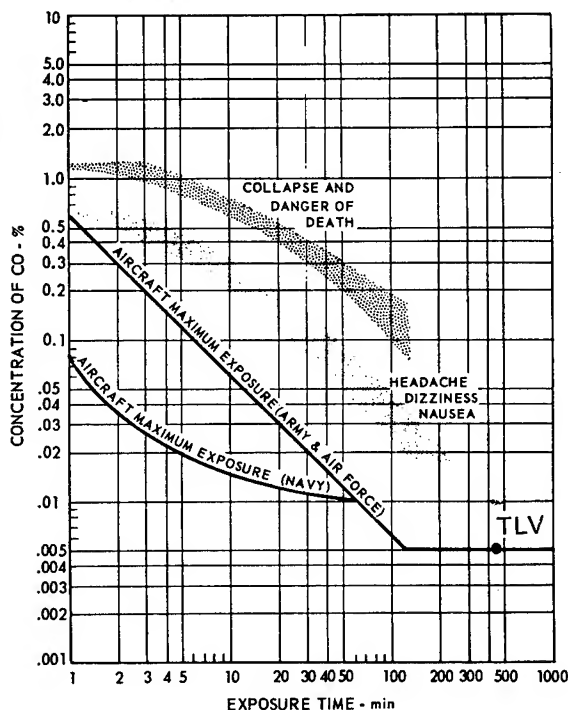


Figure 13-21
Carbon Monoxide

This graph shows the effects of carbon monoxide on man as functions of concentration and exposure time. Milder effects are shown as a lightly shaded band of exposure times and concentrations, while dangerous or lethal times and concentrations are grouped in the heavily shaded band. The solid lines are the exposure limits set by the military services for aircraft. The point marked at 0.05% CO (50 ppm) and 480 minutes is the current Threshold Limit Value (TLV) for 8-hours-a-day exposure in industry.

(After Back and Pinkerton⁽⁸⁾, adapted from Department of Defense⁽⁴⁶⁾, Haldane⁽⁷⁶⁾, Henderson and Haggard⁽⁸⁵⁾, and Sayers et al⁽¹⁷⁸⁾)

Sampling and Analysis of Toxic Contaminants

In view of the numerous compounds at low concentrations, sampling and analyses for toxic contaminants in spacecraft is a difficult problem. Sampling techniques are being improved (21, 49, 155, 207). Analytic techniques are numerous but often give variant results for the same atmosphere (36, 45, 129, 130, 155, 182). Gas-chromatographic techniques have been the most commonly used. Current studies of infrared spectroscopy interferometry (19, 53, 182), double-resonance microwave spectroscopy (197, 216), mass spectrometry (166, 207), and other new techniques (49, 66) offer some promise for ground-based and possibly inflight sampling and analysis. Sampling of water supplies for organic atmospheric contaminants (190) and inorganic contaminants (137, 191) in space cabins is covered in Water, (No. 15).

PARTICULATES AND AEROSOLS

Many of the toxic materials covered above may be in particulate or aerosol form. Even nontoxic particulates may be a hazard in space operations because of the zero gravity environment (22). In reviewing toxic hazards, one must be concerned with the fact that aerosols can act as condensing nuclei for toxic gases (180, 214). This facilitates the entrance into the lower respiratory tract of such materials which, because of their high water solubility, are generally trapped in the upper respiratory tract. It also provides for local areas of extreme irritation due to the concentration of the toxic gas in a finite area.

The aerosols may be classified as shown in Table 13-22. Generally, aerosols have a diameter of less than 50μ . The usual range is from 0.01μ

Table 13-22
Classification of Aerosols

<u>Smokes:</u>	Usually solid particles of carbon resulting from the burning of carbonaceous material. Carbon smoke is composed of particles about 0.01μ which tend to coagulate or agglomerate rapidly into long, irregular filaments several microns in length.
<u>Dusts:</u>	Solid particles ranging in size from 0.1μ or less, which produce a haze, to large particles found in a sandstorm which are likely to be the size range considered to be aerosols.
<u>Fogs:</u>	Liquid droplets generated by atomization or condensation of volatile substances on minute nuclei. The size of these particles is often quite large, ranging from 4 to 40μ , as in a natural water fog.
<u>Fumes:</u>	Solid particles generally produced by sublimation, combustion, or condensation, usually between 0.05 and 0.5μ . Fumes are produced by arcing at high temperature.

(After Punte⁽¹⁴⁸⁾)

to 10μ . Surface air on the Earth contains a considerable aerosol load. The problem, unique in the closed living space, is the tendency of these to increase in numbers and mean diameters. In submerged nuclear powered submarines the concentration reached a steady state concentration of about $0.4\mu\text{g/L}$ at approximately 100 hours (102). This compared unfavorably with the aerosol concentration in Los Angeles on a smoggy day where the concentration averaged $0.2\mu\text{g/L}$. Also there was approximately 8 times the content of organic aerosols in the submarine.

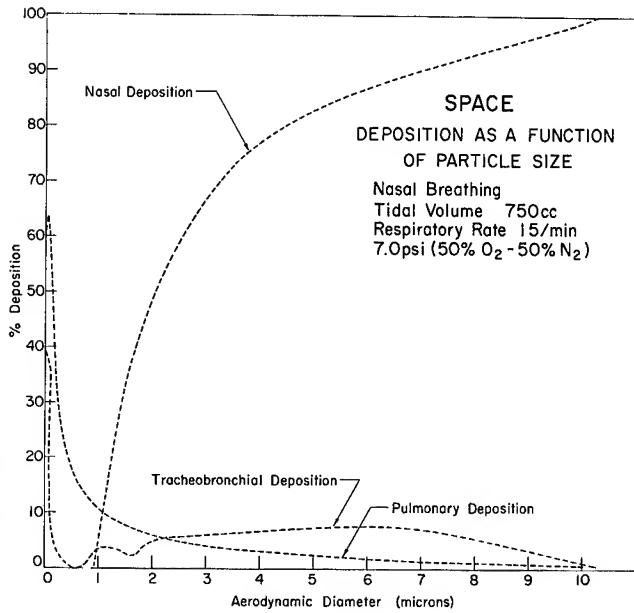
Factors influencing the stability of aerosols may be altered in the space vehicle, but the exact nature of atmospheric, electrostatic, and other effects are not clear. Under 1 g conditions on Earth, total retention of particles in diameter size 0.2μ to 5μ varies between 20 and 90%. Of the particles gaining entrance to the lower respiratory tree, the maximum particle load at that site is at the 1μ diameter level. The size which is least retained is 0.4μ . The disposition of deposited particles depends on their solubility. Those which reach the lower respiratory tract and are water soluble are rapidly absorbed into the blood stream and a toxicologic effect may occur in a short term. Less soluble substances and those deposited on the airway are moved by the flow of mucous and ciliary movement to the pharynx, where they are swallowed and excreted from the gut.

The lack of gravity will probably have an effect on the site of deposition of aerosols (22, 133). Figure 13-23a represents calculation for respiratory deposition sites for particles of different aerodynamic diameter in space cabins at zero g. Figure 13-23b shows similar calculations for the Earth environment. Figure 13-23c compares total deposition in orbiting spacecraft vs. Earth environment. Substitution of helium or another gas for nitrogen would, in this pressure range, alter viscosity by only a few percent, and hence should not alter these "deposition curves" significantly. The deposition

Figure 12-23

Comparison of Theoretical Deposition of Aerosols in Space Cabin Atmospheres
at Zero Gravity and in Air at Earth Gravity as a Function of Particle or Droplet Size

(After Busby and Mercer (23))



a. In the Space Cabins Atmospheres
in a Weightless Environment

b. In Air at One Atmosphere in a 1G
Environment

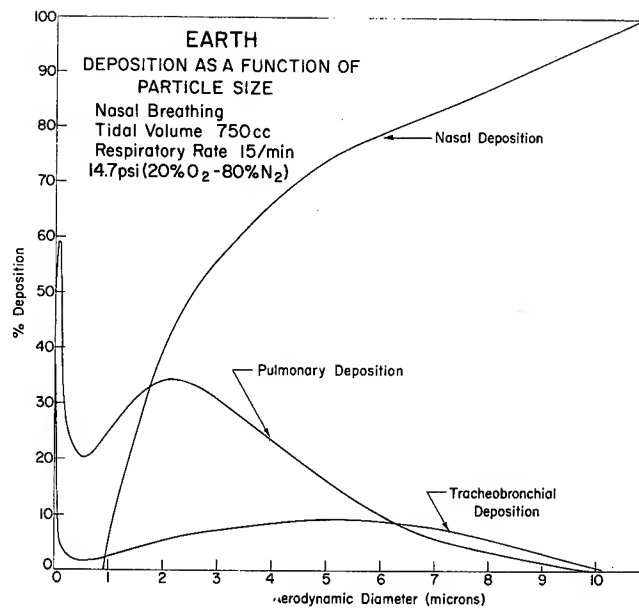
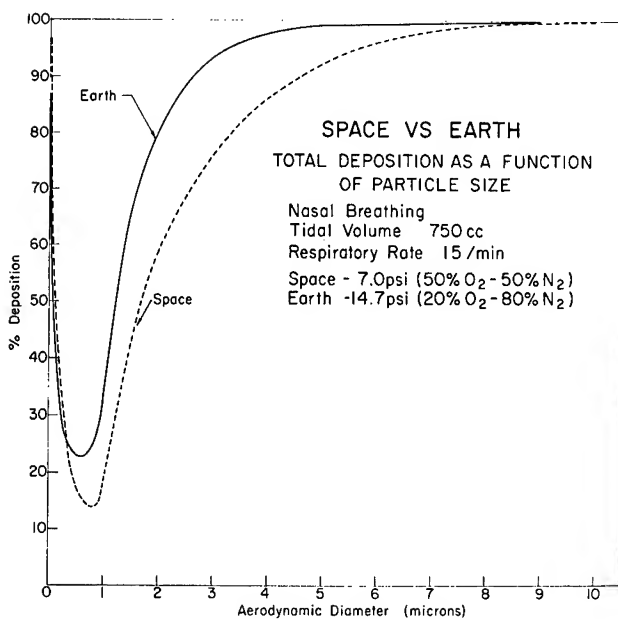


Figure 12-23 (continued)



c. Comparison of Total Deposition as a Function of Particle or Droplet Size in the Earth (Unit Gravity) and Space (Weightless) Environment

rates have been adjusted for differences in pressure between the cabin and the Earth. There are no definitive empirical data to support these theoretical curves.

Theoretical considerations of the role of zero gravity in generation of aerosols imply that the amount of particle or droplet contaminant inhaled in orbit could be increased over the amount inhaled in a similar situation under one-gravity environment (22, 23). The predicted characteristics of particle and droplet deposition in the respiratory passages for the weightless environment show that in space, as on Earth, the nose or mouth should continue to operate as highly efficient filters, protecting the lower respiratory passages from all particles and droplets above about 10 microns in diameter. Fortunately, this size is considerably less than that of particles and droplets of most contaminants which may be introduced into the spacecraft cabin atmosphere. In this respect, it should be pointed out that the use of powdered chemicals of particle sizes greater than 10 microns in space would be an important safety measure.

It is possible for an astronaut to be exposed to aerosols and droplets (e.g., liquid ejected as a fine spray) less than about 10 microns in diameter. The "deposition curves" predict that fewer inhaled particles and droplets between about 0.5 and about 10 microns in diameter will be deposited in the lower respiratory passages, especially in the pulmonary region, (Figure 12-23a vs. 12-23b) in the weightless as compared to the one-gravity environment. This implies that weightlessness might offer some protection to an astronaut from certain contaminants which, if inhaled in a similar concentration in a unit gravity environment, would be irritating to or damage alveoli

and respiratory bronchioles, or produce systemic toxic effects by being absorbed. It is of interest to note that weightlessness exerts its greatest protective effect in the pulmonary or non-ciliated region of the respiratory passages -- a region where deposited contaminants are not moved out of the respiratory passages by ciliary action. The zero-gravity deposition patterns imply that the concentration of particles and droplets one micron in diameter inhaled into the respiratory passages in the weightless environment could be approximately doubled before the percent deposition of such contaminants in the pulmonary region in this environment would be equivalent to their percent deposition in the unit gravity environment. Similarly, the inhaled concentration of particles and droplets could be increased by approximately 6 times for particles and droplets 2 microns in diameter, 7 times for those 3, 4, and 5 microns in diameter, 6 times for those 6 microns in diameter, 5 times for those 7 and 8 microns in diameter, and 3 times for those 9 microns in diameter. However, even though it is predicted that the pulmonary deposition of inhaled particles and droplets between about 0.5 and about 10 microns in diameter will be significantly reduced in the weightless environment, one must remember that such contaminating particles or droplets could still be suspended in a concentration which would be harmful.

Since the weightless space-cabin environment does not alter the high percent deposition of particles and droplets below about 0.5 microns in diameter in the lower respiratory passages, the consequences of inhaling such contaminants will probably not be different as compared to the one-gravity sea-level air environment. Contaminants of this size are most likely to be in the form of fumes or smoke. Since particles or droplets below 0.9 microns in diameter will apparently not be deposited in the nasal (or oral) regions of the respiratory passages, their inhalation should not produce clinical problems in the upper respiratory passages. On the other hand, because of the very high percent deposition of particles and droplets below about 0.5 microns in diameter, tracheobronchial and pulmonary tissues could be selectively irritated by particles of this size.

Whether or not particles or droplets larger than a few hundred microns in diameter (e.g., several hundred microns to 1 cm) can be inhaled will depend less on particle and droplet size, and more and more on such important factors as particle or droplet shape and density, their spatial relationship to the inspiratory air stream and mouth and nasal openings, their velocities and directions of movement relative to an astronaut, the velocity-time profiles of the inspiratory and expiratory air streams, and the duration of the pause between inspiration and expiration (22). Taking all of these factors into consideration, it is predicted that various particles, especially those of low density, and droplets of possibly up to 1 cm in diameter, could very well be inhaled in the weightless environment. Accordingly, it is thought that as compared to on Earth, an astronaut in space might run a somewhat higher risk not only of inhaling large particles and droplets into his nose and mouth, but also of aspirating large particles and droplets of up to 1 cm in diameter into his lower respiratory tract. The medical significance and treatment of emergencies to the respiratory tract, skin and eye from particulates in space cabins has been recently reviewed (22).

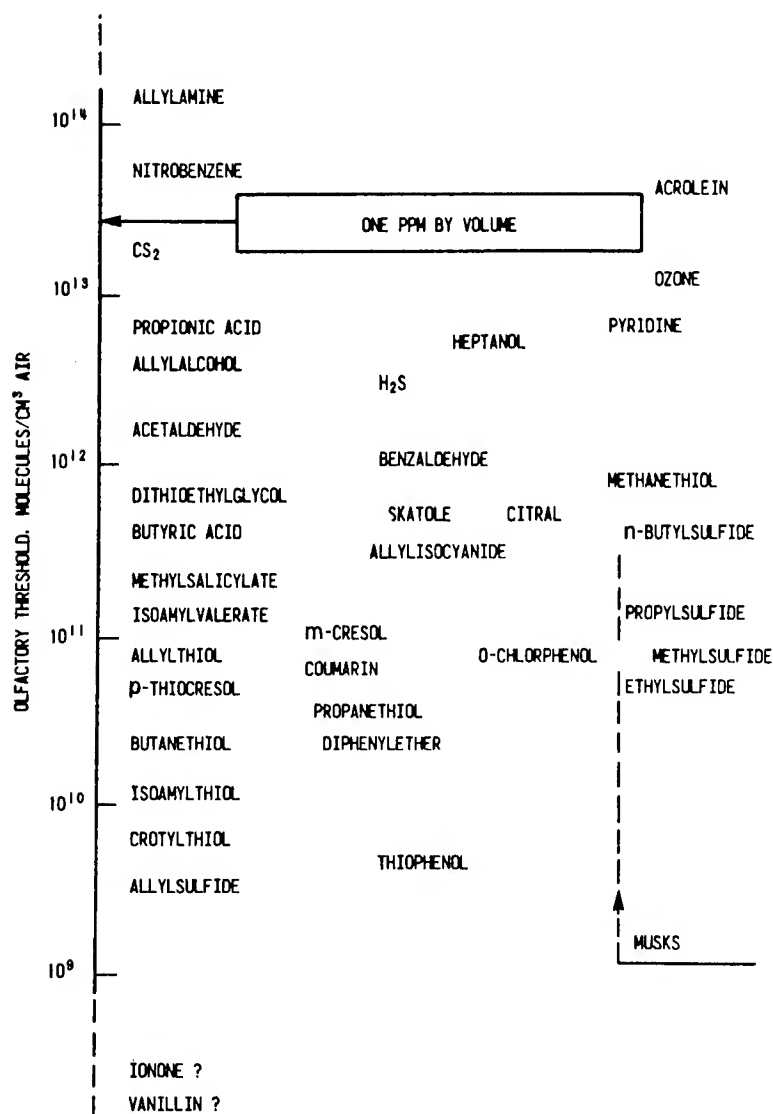


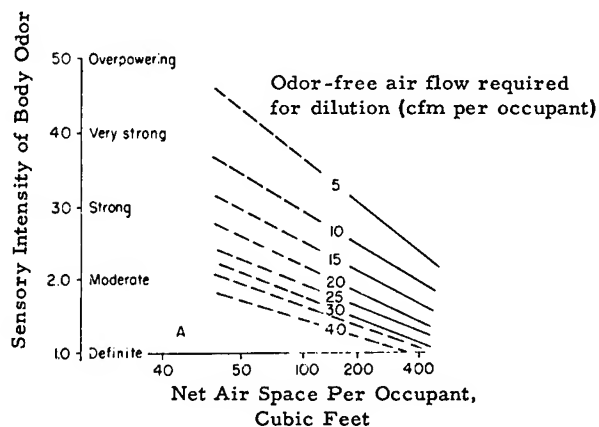
Figure 13-24
Olfactory Thresholds
(After Dravnieks⁽⁴⁸⁾)

Figure 13-25

Ventilation Requirements in Relation to Net Air Space and Body Odor

The graph shows that the intensity of body odors in a given area depend on the rate of flow of odor-free air. The solid portions of the curves are based on experimental data; the broken parts are extrapolations to the conditions found on aircraft.

(After Yaglou et al⁽²³²⁾)



Ionized aerosols have often been discussed as a cause of behavioral changes during various meteorological phenomena (105, 106) and with certain air conditioning devices (9). Other biological effects such as on tracheal cilia and lower biological forms have also been reported. The concentration of aerosol ions in the natural or submarine atmospheres has always been low. In nuclear submarines, sparking electrical equipment and radium dials were probably responsible for ion concentrations of less than $1000/\text{cm}^3$ averaging about 450 (+) ions and 250 (-) ions/ cm^3 (102). No data have been obtained in operating space cabins. In view of the low concentration of aerosol ions in submarines, the uncertain significance of the experiments with isolated tracheal preparations, and equivocal results of studies with human behavior (9, 105, 106, 140) the potential significance of these aerosols in space cabins is not clear. Presence of ozone in the outflow of generators using high voltage gradients to direct ions generated by radioactive isotopes or using spark discharges to generate ions is a problem which must be eliminated in future experiments.

Odors in Space Cabins

The human olfactory sense permits detection of vapors of many organic substances at concentrations of 10^{11} to 10^{13} molecules/ cm^3 of air and some at concentrations as low as 2×10^9 molecules/ cm^3 (48, 61). Table 13-24 represents several known odor thresholds. Indications also exist that substances at one-tenth of the threshold may influence the odor quality of other odorants present at concentrations well above the threshold (99).

Fortunately, the human olfactory sense adapts to odors quite rapidly (70). Experience in space cabins and space cabin simulators suggests that crews are not bothered by odors in the cabin which may overwhelm new additions to the crew. Data are available on odor control and the atmosphere exchanges required for elimination of body odor in a densely populated space (143, 232). This is shown in Figure 13-25. A thorough review has been made on the use of the olfactory sense in detecting and diagnosing malfunctions in equipment systems (70).

MICROBIAL CONTAMINANTS

The microbial flora of the space cabin represent particulate contaminants which can have significant effects on crew and equipment. The human, is of course, the major source of microbes in the space cabin. The normal bacterial flora on the skin, mucous membranes and intestines of man have received a recent thorough review (153). Special emphasis is given to the differences in flora of various body sites. The control of the waste management system depends on the knowledge of the microbial environment. The clogging of filter beds after prolonged exposure may be an engineering problem. Alkali superoxide beds receive bacteria from the gas stream, but the effect is mostly physical rather than chemical (20). Especially in tropical climates, microbes can cause deterioration of electronic components.

Microbial contamination of drinking water is a major problem covered in Water, (No. 15). In case of unavoidable contamination of water supplied by bacteria, organic halogen compounds may be used for sterilization (75, 127). However, optimum concentrations of the agents and modes of dispensing depend on the level of reducing agents present along with the bacteria and thus require empirical study for spacecraft application. Heat appears to be the best solution to date (137, 191).

Space cabins with their limited space and hygienic facilities tend to increase the problem of bacterial control. Studies performed in sealed cabins suggest that there is an increase in the total skin flora especially in axillary, groin, and other fold areas (18, 63, 64, 68, 84, 117). This tendency is increased by the wearing of a space suit and by high humidity (64). The buildup tends to reach a plateau after variable periods of time in a given environmental situation. There is an exchange of fecal and dermal flora between enclosed subjects with no tendency for pathogens to become predominant. Throat flora are exchanged less rapidly (84).

Increase of atmospheric P_{O_2} to 5 psia 100% oxygen tends to produce a variable increase in the percent of skin aerobes (84, 153). Fecal flora retain a predominant percentage of anaerobes which continue to contaminate the skin. Buildup of organisms on the wall and furniture of the chambers is predominantly staphylococci, Gram negative rods and streptococci in both high and normal oxygen environments (18, 64). Within space suits in 100% oxygen with minimum hygienic procedure, the bacterial count of the body reaches a maximum in about one week and remains elevated or declines thereafter. Wearing of suits does not seem to alter the components of the flora (64).

The major sources of bacterial contamination in a space cabin are from fecal material and skin. Much dry weight of the stool is bacteria. Alteration of the normal bacterial flora by different space-food diets has been covered in Nutrition, (No. 14). Basic data may be found in References (26, 38, 58, 96, 117, 121, 132, 152, 154, 189). Fecal flora tend to retain their person-to-person individuality much more than do those of the skin. An occasional black slime-and-gas-forming prophalactic anaerobe is found (62, 63). In actual space flight, there appears to be an increase in the number of bacteria in the craft and on the astronauts' skin and mucous membranes (229).

Little is known about the viral population in sealed systems (229). Subtle interactions between the gaseous environment and host may alter viral infectivity (69).

To date, there has been no tendency for an increase in pathogens or a decrease in body resistance to pathogens in chamber studies under minimal hygienic conditions (117, 118, 119, 120). Pathogens have been transferred from subject to subject with no outbreak of infection (63). Presence of 100% oxygen at 5 psia does not appear to alter grossly the susceptibility of animals to infections by pathogens (229). The isolated spacecraft environment would be expected to eliminate exogenous disease. Radiation and subacute stress may alter response to infection in some future missions but no problems have arisen to date. In nuclear submarines with large crews, there tends to be a

flurry of infectious disease of primarily respiratory type in the first few weeks of a cruise but this incidence drops rapidly as "herd immunity" is developed (229). This pattern may be expected in large space crews of the future.

An interesting finding in recent studies was death in several animals following administration of tetracycline drugs when in a 100% oxygen 5 psia atmosphere (202). It is only presumed that tetracycline was the prime factor, but the finding of a possible altered toxicity to a drug in this atmosphere requires further study.

The problems of sterilizing spacecraft components for avoiding microbial contamination of other planets and to avoid back-contamination of Earth are now under study (10, 16, 39, 55, 59, 91, 95, 98, 108, 109, 110, 111, 112, 113, 114, 124, 128, 143, 171, 181, 233). Data are also available on the leakage of bacteria from pressurized space suits (211).

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14. NUTRITION

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NUTRITION

For missions of duration no longer than 30 days, it has been recommended that dietary needs of man in space are essentially those of men of similar physical stature on earth (25,92). Extension of this approach to longer missions cannot be made with any degree of assurance. A more thorough understanding of physiological and environmental problems related to nutrition is required before recommendations can be made for dietary packaging and storage design in missions of long duration.

Basic Nutritional Requirements

The data of Figure 14-1 represents the allowances for normal maintenance and performance as well as prevention of disease which the Food and Nutrition Board of the National Academy of Science-National Research Council has recommended. These allowances, which are at present under review by the NAS-NRC, all exceed the minimal maintenance requirement with the possible exception of energy.

Table 14-1

Recommended Daily Dietary Allowance for Average U.S. Male Performing Moderate Physical Activities in a Temperate Environment

(After NAS-NRC (67))

Age (years)	Weight (kg)	Height (cm)	Calories (kcal)	Water	Protein (gm)	Fat (gm)	Carb (gm)	Calcium (gm)	Iron (mg)	Vit A (I. U.)	Thiam (mg)	Ribo (mg)	Niacin (mg equiv)	Ascorbic Acid (mg)
25	70	175	2900	1 ml/kcal expended	70	97	437	0.8	10	5000	1.2	1.7	19	70
35-55	70	175	2600	1 ml/kcal expended	70	85	389	0.8	10	5000	1.0	1.6	17	70

In addition to these allowances, it has been suggested that the energy requirements of the Apollo mission and anticipated stresses of space flight can be met with the following alterations to the NAS-NRC recommendations (11):

- Energy. 2800 kcal/man/day.
- Protein. NAS-NRC recommended allowance of 1 g/kg of body weight/day. For the present population of astronauts, the diet should therefore contain 10.5 to 13.0 gm nitrogen/man/day.
- Fat. Maximized to conserve weight and space but limited to 150 g/man/day and 50 percent of total calories to avoid physiological consequences such as ketosis and nausea.

- d) Carbohydrate. Content of poorly digested carbohydrates minimized to decrease intestinal fermentation and fecal residues; crude fiber content limited to 1 percent of total dry solids.
- e) Water. The water requirements for space operations exceed in many situations, the 1 mg/kcal recommended as a standard allowance for temperate climates. (See Water, No. 15.)
- f) Minerals. (bulk). The NAS-NRC recommended allowances are adequate: (in g/man/day) calcium, 0.8; phosphorus, 1.2; magnesium, 0.35; sodium, 4.0; potassium, 3.0; iron, 0.10. It has been recommended that water consumption of >4 liters/day would require 1 gram additional NaCl for each liter of water (23). Potassium should be limited to about 1 gram/1000 cal/day.
- g) Vitamins. To be given as a separate tablet or capsule. The following supplement, per man/day: thiamine, 2 mg; riboflavin, 3 mg; niacin, 20 mg; pyridoxine, 5 mg; pantothenic acid, 10 mg; folic acid, 0.5 mg; vitamin B₁₂, 2 µg; biotin, 0.5 mg; choline, 1 g; vitamin A, 4000 U.S. P. Units; vitamin D₂, 400 U.S. P. Units; vitamin K₁, 1 mg; ascorbic acid, 70 mg; and alpha tocophero, (?) 1 gm/day. (See below.)

The protein level may be higher and the B₁₂ lower than new NAS-NRC allowances may specify (8). It should be recognized that addition of these vitamin supplements are quite in excess of the recommended NAS-NRC allowances (23). They undoubtedly will not produce toxic or undesirable effects, but may really serve no useful purpose (48). They have been recommended to cover any unanticipated environmental or operational condition which may affect the storage or metabolic utilization of vitamins in the basic diet. Starvation is another consideration which must be anticipated. (See below.)

The need for an important vitamin supplement to this diet has been prompted by the finding of hemolysis in the crews of the Gemini program associated with exposures to atmospheres of 5 psia - 100% oxygen and simultaneous deficiency of tocopherol in the plasma (3, 27). Similar tocopherol deficiencies in the diet and plasma of test subjects fed "Gemini diets" for 6 weeks have also been reported (8). (See discussion of Table 10-41.) The similarity of the hematological findings to those of vitamin E responsive anemias (20) and the autohemolysis (red cell destruction) of acanthocytosis (a hereditary disease of red cells with spiked surfaces) (47) suggests that supplementation of the diet with high levels of tocopherol and other antioxidants may offer prophylaxis against the blood disorder. Daily intakes of 1 gm of tocopherol /day for 2 weeks have increased plasma and adipose tocopherol levels several fold without toxic side effects (59). Studies are required to determine if such supplementation is actually effective in altering the blood disorder or restoring plasma tocopherol to normal levels in actual or simulated flights. Further supplementation of ascorbic acid and other antioxidants should be considered.

Factors affecting energy utilization and requirements for protein, carbohydrates, vitamins and minerals in flights of longer duration have been discussed, but more definitive experimentation is required before formal recommendations can be made (13, 23, 33, 98).

- h) Trace minerals. The use of a variety of foods in the diet will assure the presence of at least some trace minerals. It is unlikely that an influence of marginal supply of these would be manifest in several weeks, but it would be desirable to ascertain mineral and water content so that intake level may be known for future reference.

In case of mission contingencies with high potential for stressful environmental and exercise variables, consideration of optimum diets and survival rations is in order (13, 14, 16, 19, 52, 79, 89, 90, 97, 100, 103). These nutritional factors may play a role in prolonging life until rescue is possible. New high-energy, non-fat nutrient sources are being studied for survival rations and diets where logistic problems are present (64). The relationship between the composition of food and obligatory minimum water requirements is discussed in the section on Water, (No. 15).

The use of algae and bacteria as food in regenerative life support systems has been recently reviewed (68, 69).

Metabolic, Logistical, and Operational Trade-Offs

The manipulation of dietary components to solve logistic and other operational requirements is based on an understanding of the weight, volume, energy, gas, and other tradeoffs (78, 96, 102). The following data present a basis for these tradeoffs.

Metabolic Factors

Metabolic processing of various food mixtures can be described quantitatively in a series of equations for which the numerical constants have been empirically derived. Two basic assumptions are: (a) all of the food used is carbohydrate, fat, or protein, each of which is characterized accurately enough by a single set of average properties; (b) all foods are reduced to standard end-products, namely, carbon dioxide, water, and urinary nitrogen. From the equations of Table 14-2, one may predict for any given mixture of carbohydrate (C), fat (F), and protein (P); the heat energy (H) produced in the body, the oxygen (O_2) consumed, and the carbon dioxide (CO_2), water (W) and the urinary nitrogen (N) excreted.

In using these equations as well as the graphs and nomograms which follow, it should be realized that the greater the deviation from the normal dieting preparations, the more insecure these data become. Not enough is really known about the subtle interactions which may arise with use of some of the abnormal ratios presented in these figures. Nutritional experts should be consulted for permissible limits of composition when use of any abnormal mixture is anticipated.

Figure 14-3 shows the effect of changing the constituent proportions of a 2800 Calorie (kcal) diet on the weight of the food (without packaging), the oxygen required for metabolism, and the resulting CO_2 and water.

Table 14-2
Metabolic Factors Related to Composition of Food
(Adapted from McHattie⁽⁵⁸⁾)

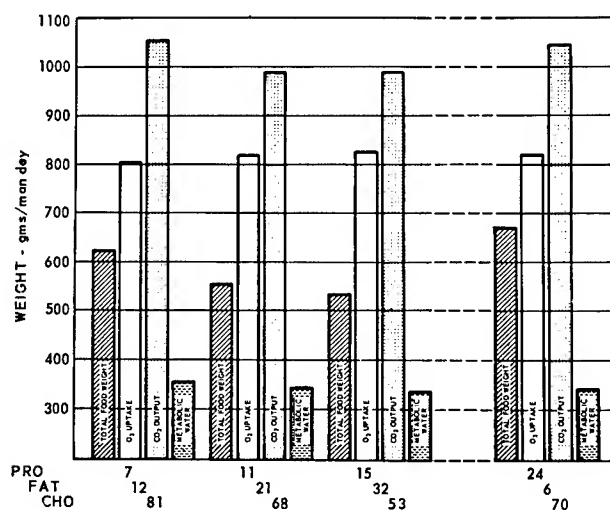
$$\begin{aligned} H &= 4.182C + 9.461F + 4.316P && \text{in kcal/unit time} \\ O_2 &= 0.829C + 2.019F + 0.967P && \text{in liters/unit time} \\ CO_2 &= 0.829C + 1.427F + 0.775P && \text{in liters/unit time} \\ W &= 0.555C + 1.071F + 0.413P && \text{in grams/unit time} \\ N &= 0.1628P && \text{in grams/unit time} \end{aligned}$$

where

C is carbohydrate metabolized in grams/unit time

F is fat metabolized in grams/unit time

P is protein metabolized in grams/unit time



Proportions of $\left\{ \begin{array}{l} \text{Protein} \\ \text{Fat} \\ \text{Carbohydrate} \end{array} \right.$ in a 2800 kcal Diet (% of total kilocalories)

Figure 14-3
Metabolic Effects of Altering the Components
of a 2800 kcal Diet
(Adapted from Wu and Yakut⁽¹⁰²⁾ by Finkelstein⁽²⁵⁾)

Figure 14-4 shows the changes in food weight, oxygen consumption, CO₂ production, and metabolic water which result from changing the composition of a fixed protein diet. When the protein intake is 12%, the effect of changing the proportions of carbohydrate and fat is that more oxygen is needed to metabolize a high fat diet and less CO₂ is produced. The weights of the food and of the metabolic water decrease as the proportion of fat increases. (See also Oxygen-Carbon Dioxide-Energy, No. 10).

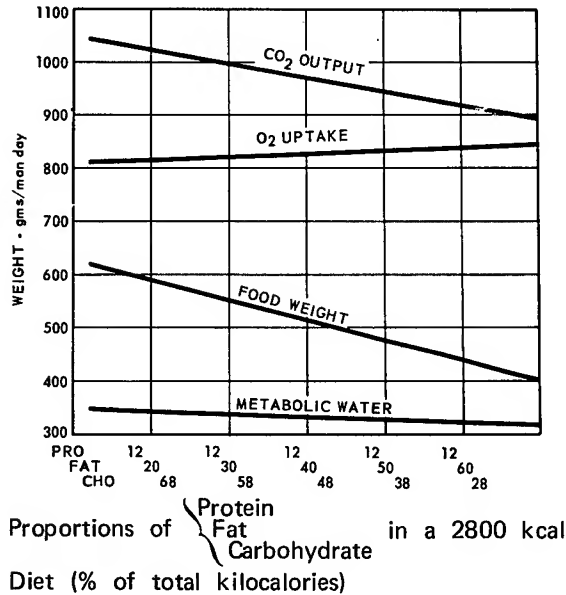


Figure 14-4

Metabolic Effects of Altering the Components of a 2800 kcal Diet with Fixed 12% Protein

(Adapted from Wu and Yakut⁽¹⁰²⁾ by Finkelstein⁽²⁵⁾)

Figure 14-5a shows the effect of the carbohydrate:fat weight ratio (w_c/w_f) on the gross weight of food intake per man-day for a diet of 3000 kcal/man-day (12 KBTU/man-day) with different ratios of protein to fat weight (w_p/w_f). The interior chart gives correction factors for diets other than 12 KBTU/man-day which are multiplied by the ordinate to give appropriate gross food weights. The data are in more useful engineering terms than those of Figures 14-3 and 14-4. The figure assumes that the heat of combustion of carbohydrate is 7.10 KBTU/lb protein-7.15 KBTU/lb and fat - 16.25 KBTU/lb and that the energy balance equation is:

$$7.1 w_c + 7.15 w_p + 16.25 w_f = 12 \text{ KBTU/man-day} \quad (1)$$

Figure 14-5b represents data similar to those of Figure 14-4 for a diet of 3000 kcal/man-day or 12 KBTU/man-day. It permits a rapid evaluation of the total mass of food plus respiratory gases supplied to an astronaut per day. Permitted to cover a wide range of possible diets, it is shown as a series of curves including a line of constant food weight. Only a single constant food line at 1.28 lbs/man-day is plotted. In addition, the respiratory quotient is also presented, which is defined as the number of pound-moles of CO₂ formed per pound-mole of oxygen burned. To equal unity implies that no hydrogen is available within the food for physiological combustion. It is observed that an unacceptable all-fat diet presents the minimum weight-of-food penalty to the space vehicle. The correction factor in the interior of Figure 14-5a may again be used to determine weight penalties for other metabolic rates in Figure 14-5b.

Figure 14-5

Weight of Diet Made Up of Ordinary Food Items That Must Be Eaten with Different Proportions of Carbohydrate, Fat, and Protein to Provide 3000 Calories/Day

(After Rutz⁽⁷⁸⁾);

a.

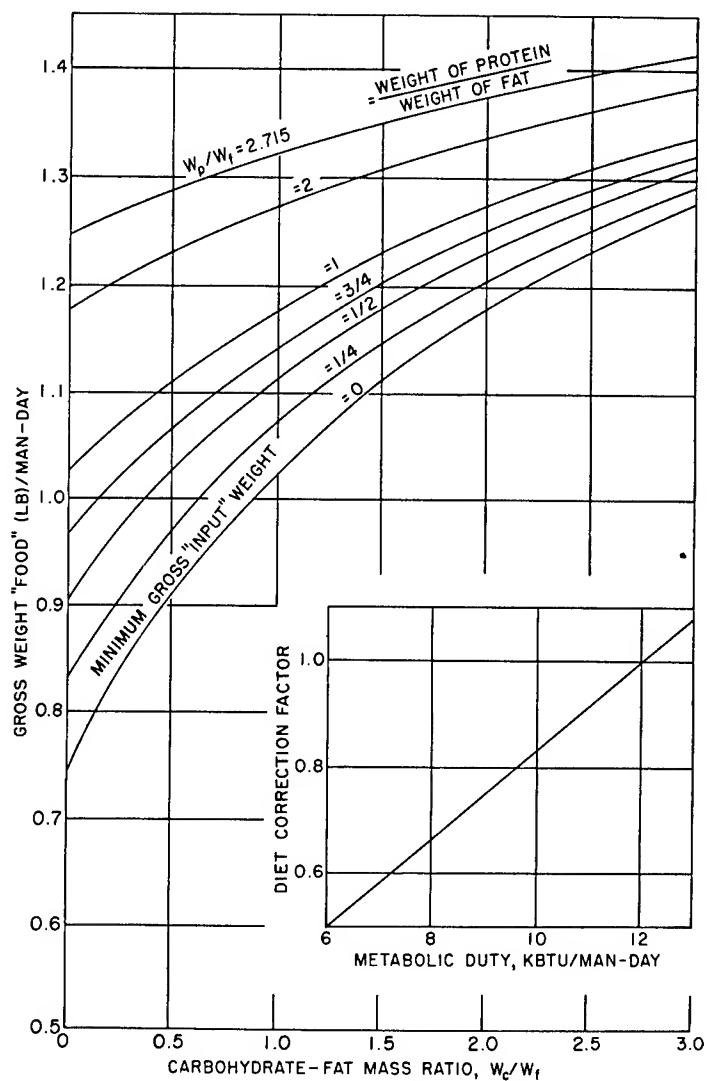
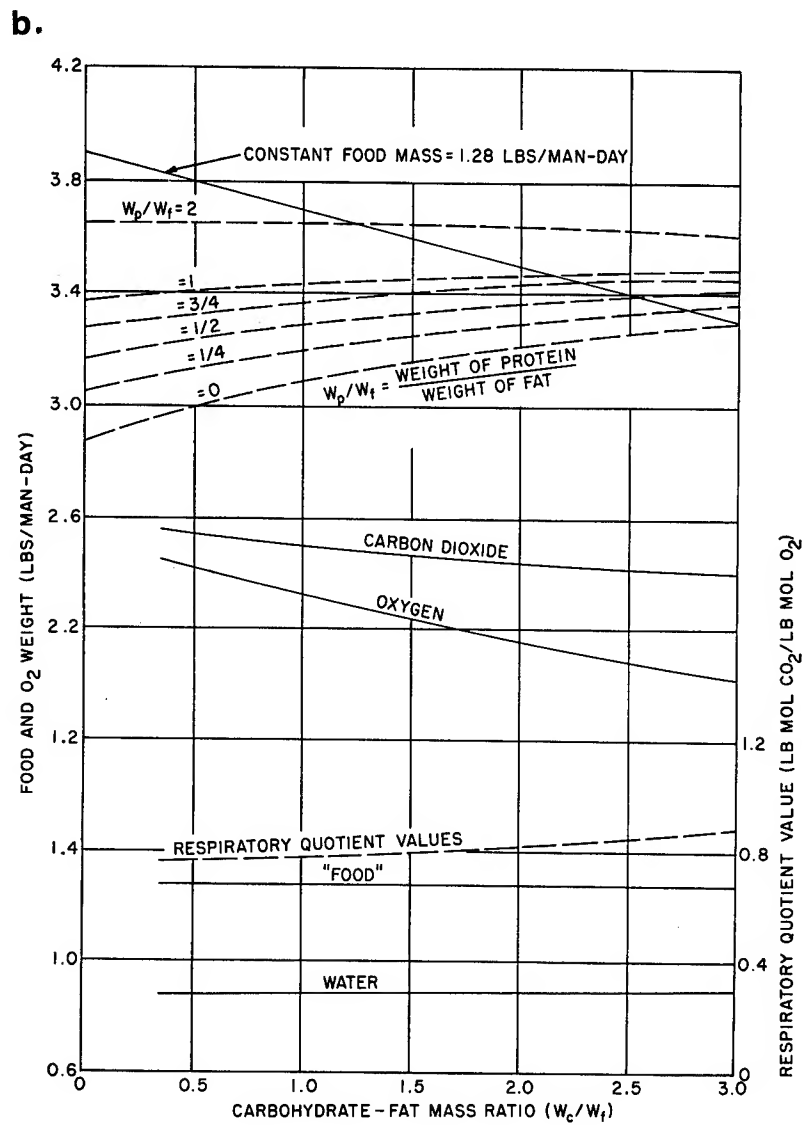


Figure 14-5 (continued)



A detailed review of metabolic interchanges in synthetic diet construction is available (18). Figures 14-6a to i are nomograms which permit rapid evaluation of these basic interchanges. The utility of the individual nomogram is clarified by the use of detailed descriptions of the manipulations required to solve typical problems. These explanations are an integral part of each figure.

- Figure 14-6a: Dietary protein requirements based on body weight in pounds or kilograms.
- Figure 14-6b: Percent calorie distributions of carbohydrate, fat, and proteins at total caloric intakes of 3200-2000 Kcalories per day.
- Figure 14-6c: Gram or pound quantities of all possible ratios of carbohydrate, fat, and protein to supply a daily caloric intake from 3200 to 2000 Kcalories.
- Figure 14-6d: Complete dry diet weight (pounds) for all possible weight ratios (grams or pounds) of carbohydrate, fat, and protein in caloric range of 3200 to 2000 Kcalories/day.
- Figure 14-6e: Oxygen consumption (pounds or liters) for all possible weight ratios as qualified under Figure d.
- Figure 14-6f: Carbon dioxide production (pounds or liters) for all possible weight ratios as qualified under Figure d.
- Figure 14-6g: Metabolic water production (pounds) for all possible weight ratios as qualified under Figure d.
- Figure 14-6h: Complete dry diet (in. ³/man/day) for all possible weight ratios as qualified under Figure d.
- Figure 14-6i: Nomogram for estimating the density - volume factor required for calculating the bulk weight of the diet in lbs/ft.³ for all possible weight ratios as qualified under Figure d.

Secondary Physiological Factors

The space environment imposes several constraints for the preparation, storage, and packaging of food other than just weight and power. The behavioral aspects of food and eating must be considered (5). The number and size of meals must allow for programming of eating with task performance and provide small enough portions to prevent a large bolus of food in the stomach. The nibbling pattern frequently encountered among humans in chronic anxiety-producing situations should be satisfied. Monotony, should, however, be avoided (80, 83).

Careful attention should be given to the selection of specific foods in carbohydrate forms which minimize excessive intestinal fermentation with the resultant production of large volumes of gas (9, 38, 50, 66). Foods with irritant properties must be excluded as must those with high fiber

content to keep fecal mass to a minimum in those missions where fecal storage or removal is a problem. The alteration by space diet of fecal mass and bacterial flora should be considered (11, 24, 28, 29, 30, 43, 44, 45, 46, 56, 57, 74, 75, 81, 84, 85). This factor must be integrated with the waste management system (84, 85).

Palatability, appetite, and organoleptic qualities must be optimized (55, 62). The organoleptic properties of space diets have been measured by several hedonic scales (11, 35, 73, 80, 82, 83, 86, 88, 99). (See Tables 14-9 and 14-10 as examples.) Transfer of these values to the preferences of highly selected and highly motivated crews in the actual space environment requires further study. Formula diets of various types are also under study (11, 21, 36, 44, 61, 81, 85).

Microbiological production standards and stability of foods under the environmental background of the mission must be assured. Practical methods for evaluating production and stability standards are available (11, 22, 34, 37, 51, 70, 71, 93, 94, 95). Table 14-7c covers some of the microbial contamination limits. Data are available on the microbiology of selected dehydrated foods (100). Mechanisms of the oxidative deterioration of space foods are now under study (2, 42). Destruction of tocopherol by oxidation is a major problem. (See above.) (8, 27)

Figure 14-6

Metabolic Interchanges in Food Logistics

(After Cox⁽¹⁸⁾)

a.

A straight line drawn from a point on Scale A or B through the center of target will intersect Scale C to give a daily protein intake equivalent to one gram of protein per kilogram of body weight. This value times the desired protein level per kilogram of body weight gives the daily dietary protein requirement.

EXAMPLE OF USE

Problem - Subject weighs 184 pounds and you wish the diet to supply 1.40 grams of dry protein per kilogram of body weight. How many grams of protein should the diet supply per day?

Solution - A straight line drawn from the point 184 on Scale A through the target intersects Scale C at a protein value of 83.9 grams. $83.9 \times 1.4 = 117.5$ grams.

Answer - 117.5 grams of protein per day.

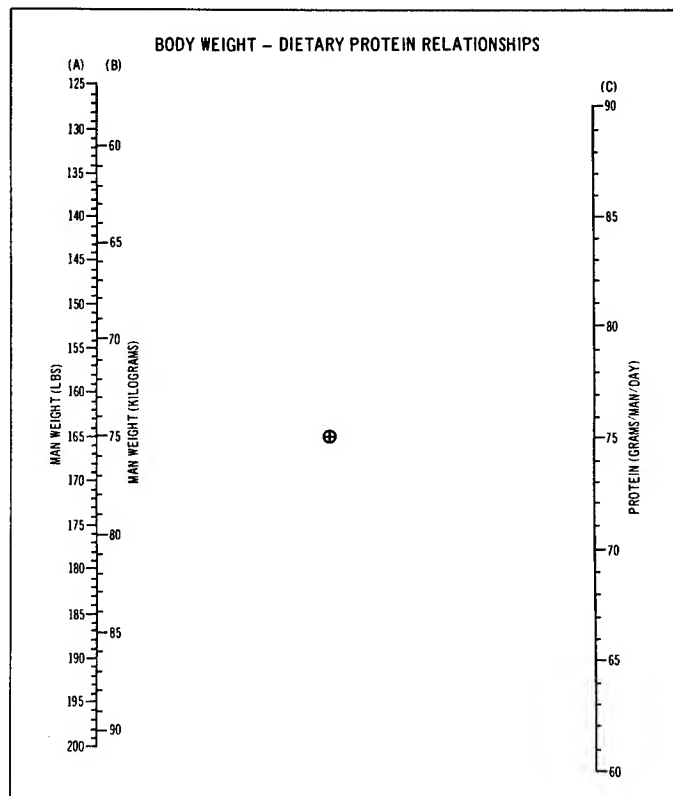


Figure 14-6 (continued)

b.

This figure was designed for the purpose of estimating the weight ratios of carbohydrate, fat, and/or protein required when the stipulation is made that a certain diet must supply a definite percentage of the total calories in the form of a certain digestible dietary constituent.

EXPLANATION

A straight line drawn from a point on Scale C through the total calorie value of the diet on Scale D will intersect Scale B to give the percent protein calories in the diet. If certain percentage of protein calories is desired in the diet, this is estimated by drawing a straight line from the desired point on Scale D through the total calorie point on Scale C. The intersect on Scale B will give the daily requirements in grams of protein per/man/day. Similar relationships exist between Scales B, B' and C for fat calories and between Scales A, A' and D for carbohydrate calories.

Example 1 - A 2800 Kcal per day diet must supply 15% of the total calories in the form of protein calories. What is the daily protein requirement in grams/man/day?

Solution - A straight line drawn from the 15 point on Scale D through the 2800 point on Scale C intersects Scale B at the 104 point.

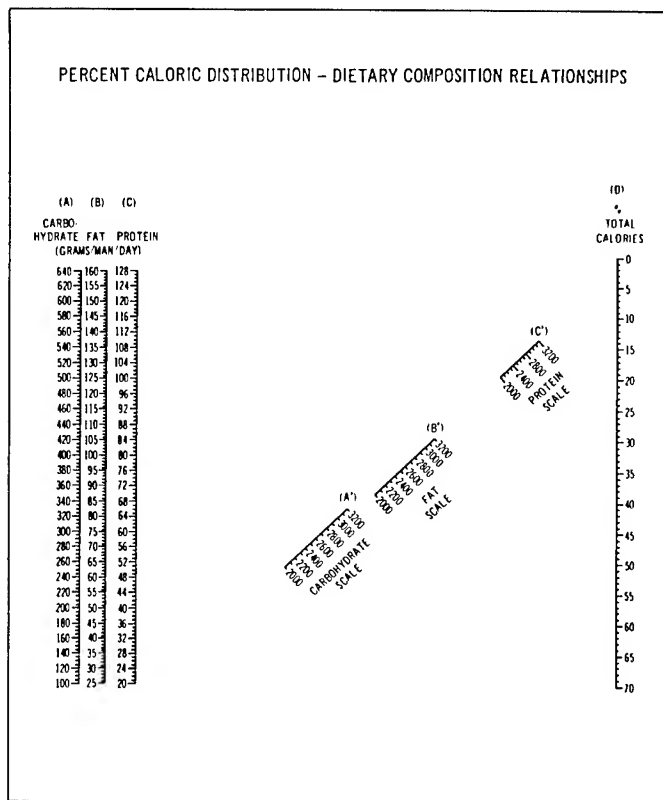
Answer - Approximately 104 grams protein/man/day required.

Example 2 - A 2500 Kcal per day diet must not contain over 40% of total calories as fat calories. What is the maximum level of fat that can be included in this diet?

Solution - A straight line drawn from the 40 point on Scale D through the 2500 point on Scale B' will intersect Scale B at the 110 point.

Answer - Approximately 110 g. fat per day is maximum level.

$$\text{check} = \frac{110 \times 9}{2500} = \frac{990}{2500} = 39.6\%$$



c.

Problem 1 - What ratios of carbohydrate, protein, and fat will supply 2800 Kcal./day?

Solutions - Any straight line drawn through the 2800 point on Scale D will intersect Scales A-B, E-F, and G-H to give, respectively, the required grams or pounds of carbohydrate, protein and fat to supply 2800 Kcal.

This relationship holds for any total K-calories/day level from 2000 to 3200.

Problem 2 - What is the total K-calorie value of any desired ratio of carbohydrate, fat, and protein? For example 350g. carbohydrate, 140g. fat and 90g. protein.

Solution - Draw a straight line from the 350g. point on Scale A through the 140g. point on Scale H. This line will intersect Scale C at the point 2650. A straight line drawn from this 2650 point on Scale C through the 90g. point on Scale E will intersect Scale D to give the desired total Kcal. value.

Answer - 3010.

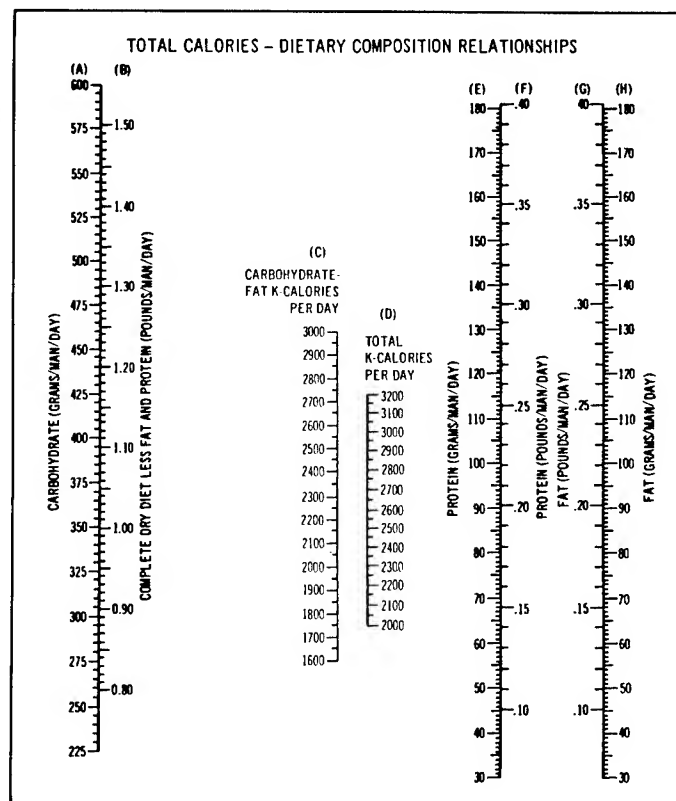
Problem 3 - A diet is designed to supply 100g. of protein and 2600 Kcal. per day. What ratios of carbohydrate and fat can be utilized to meet the caloric requirement?

Solution - Draw a straight line from the 100g. point on Scale E through the 2600 point on Scale D to intersect Scale C at point 2190. Any straight line drawn from this intersect on Scale C to intersect Scales A and G will give ratios of carbohydrate and fat, respectively, that will meet the total caloric requirements.

Problem 4 - A diet is designed to supply 1900 carbohydrate -fat Kcal. per day and a total Kcal./day level of 2600. What is the required protein level?

Solution - A straight line drawn from the 1900 point on Scale C through the 2600 point on Scale D will intersect Scale E to give the desired protein value.

Answer - 168g. protein



(Figure 14-6 (continued))

d.

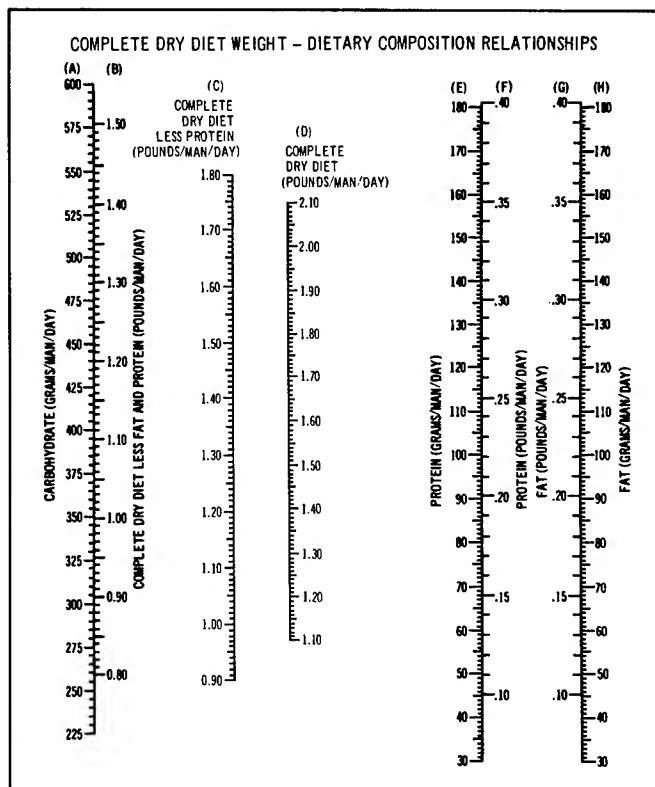
This figure was designed for the primary purpose of determining the complete dry diet weight when the weight ratios of carbohydrate, fat and protein are known. This was made possible by including in Scale B all the ingredients of a complete diet with the exception of the fat and protein. See the footnote at the bottom of this page for the dietary factors included in Scale B.

Problem 1 - What is the dry weight of a complete diet which supplies 500g. carbohydrate, 100g. fat and 70g. of protein per day?

Solution - Draw a straight line from the 500 point on Scale A through the 100 point on Scale H. This will intersect Scale C at the 1.55 point. From this point draw a straight line through the 70 point on Scale E. This line will intersect Scale D to give the answer to the problem.

Answer - 1.70 lbs.

Footnote - Scale B represents the sum of the following dietary ingredients; the indicated grams of carbohydrates; 0.20 lbs. of indigestible bulk; 13.26 g. minerals consisting of the following elements: Na - 4.2 g., Cl - 6.50 g., P - 1.26 g., Ca - 0.84 g., K - 0.42 g., S - 10 mg., Mg - 10 mg., Fe - 10 mg., and Zn - 10 mg. Trace quantities of I, Cu, Mn, Co, and Mo would be supplied as additives or contaminants with the other dietary ingredients; and 128.8 mg. of crystalline vitamins consisting of the following: Vitamin C - 77 mg., Vitamin A - 32.3 mg. B-carotene, Vitamin E - 1.5 mg. α -tocopherol, Vitamin D - 1.0 mg. 7-dehydro cholesterol, pantothenic acid - 2.5 mg., 1.5 mg. levels of thiamine, riboflavin, and pyridoxine and niacin - 10 mg., and trace (μ g) quantities of Vitamin-K, biotin, B₁₂ and folic acid.



e.

This figure was designed to determine the oxygen consumption per man per day when the weight ratios of carbohydrate, fat, and protein are known.

EXAMPLES OF USE

Example 1 - What is the oxygen consumption on a 2800 Kcal. diet consisting of 530g. carbohydrate, 44.5g. fat and 70g. protein?

Solution - Draw a straight line from the 530 point on Scale A through the 44.5 point on Scale I. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale F. This line will intersect Scale D to give the desired answer in pounds/man/day or Scale E liters/man/day.

Answer - 1.87 pounds or 593 liters

Example 2 - What is the daily oxygen consumption on a 2800 Kcal diet consisting of 275g. carbohydrate, 158g. fat, and 70g. protein?

Solution - Draw a straight line from the 275 point on Scale A through the 158 point on Scale I. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale F. This line will intersect Scale D to give the desired answer in pounds/man/day or Scale E in liters/man/day.

Answer - 1.93 pounds or 613 liters.

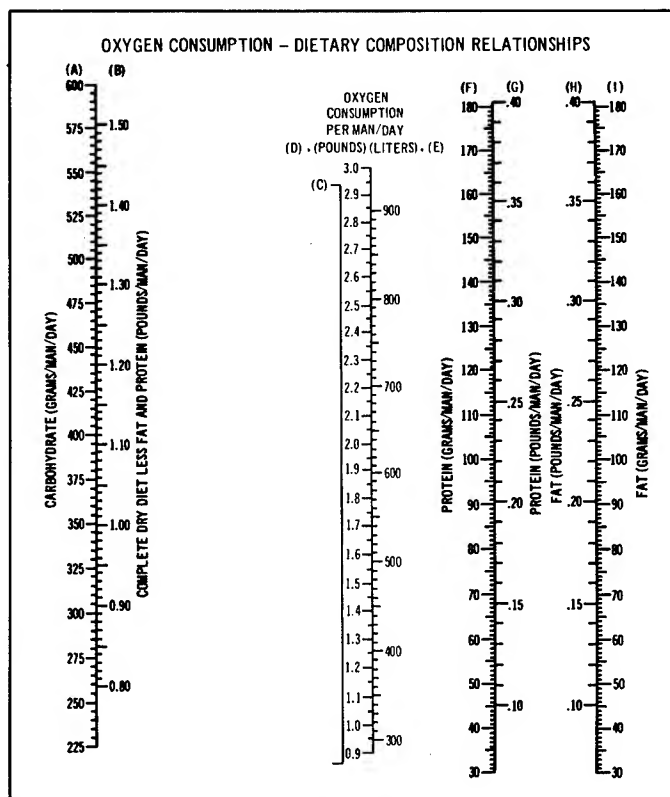


Figure 14-6 (continued)

f.

This figure was designed to determine the carbon dioxide production per man day when the weight ratios of carbohydrate, fat and protein are known.

EXAMPLES OF USE

Example 1 - What is the daily carbon dioxide production on a 2800 Kcal. diet consisting of 530g. of carbohydrate, 44.5g. of fat and 70g. of protein?

Solution - Draw a straight line from the 530 point on Scale A through the 44.5 point on Scale I. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale F. This line will intersect Scale D to give the desired answer in pounds/man/day Scale E in liters/man/day.

Answer - 2.39 pounds or 551 liters

Example 2 - What is the daily carbon dioxide production on a 2800 Kcal. diet consisting of 275g. of carbohydrate, 158g. of fat and 70g. of protein?

Solution - Draw a straight line from the 275 point on Scale A through the 158 point on Scale I. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale F. This line will intersect Scale D to give the desired answer in pounds/man/day or Scale E in liters/man/day.

Answer - 2.18 pounds or 503 liters.

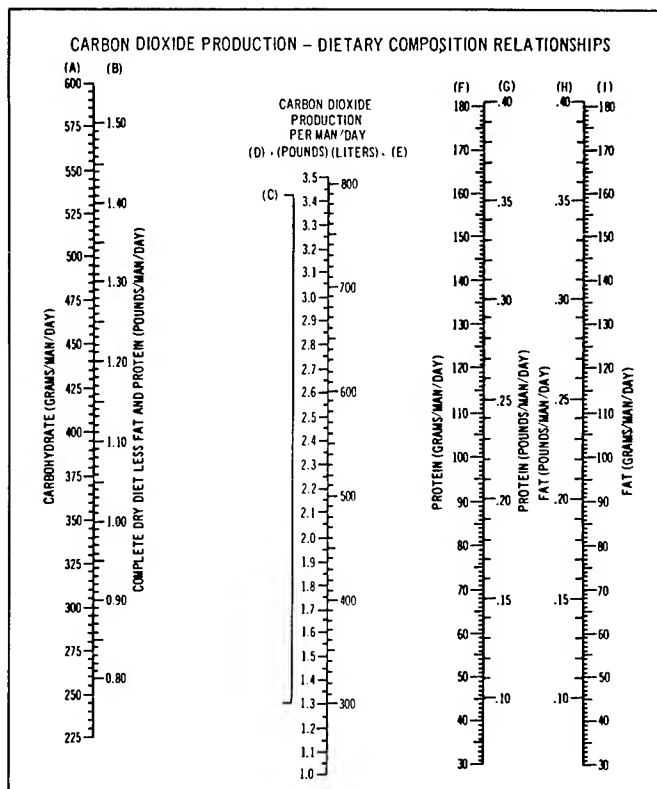
RQ DETERMINATION UTILIZING FIGURES 4 AND 5

What are the RQ values for the diets used in Examples no. 1 and no. 2 in explaining the use of figures 4 and 5?

Solution for Example No. 1 diet - The intersect on Scale E (Figure 5) gave a production of 551 liters of CO₂; the intersect on (Figure 4) showed the consumption of 593 liters of O₂.

$$RQ = \frac{\text{liters CO}_2}{\text{liters O}_2} = 0.925; \text{ for Example No. 2 diet:}$$

$$RQ = \frac{503}{613} = 0.821$$



g.

This figure was designed to determine the metabolic water production per man per day when the weight ratios of carbohydrate, fat and protein are known.

EXAMPLES OF USE

Example 1 - What is the daily metabolic water production on a 2800 Kcal. diet consisting of 530g. of carbohydrate, 44.5 g. of fat and 70g. of protein?

Solution - Draw a straight line from the 530 point on Scale A through the 44.5 point on Scale H. From the intersect formed by this line on scale C draw a straight line through the 70 point on Scale E. This line will intersect Scale D to give the desired answer.

Answer - 0.81 pounds of metabolic water man day.

Example 2 - What is the daily metabolic water production on a 2800 Kcal. diet consisting of 275g. of carbohydrate, 158g. of fat and 70g. of protein?

Solution - Draw a straight line from the 275 point on Scale A through the 158 point on Scale H. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale E. This line will intersect Scale D to give the desired answer.

Answer - 0.77 pounds of metabolic water/man day.

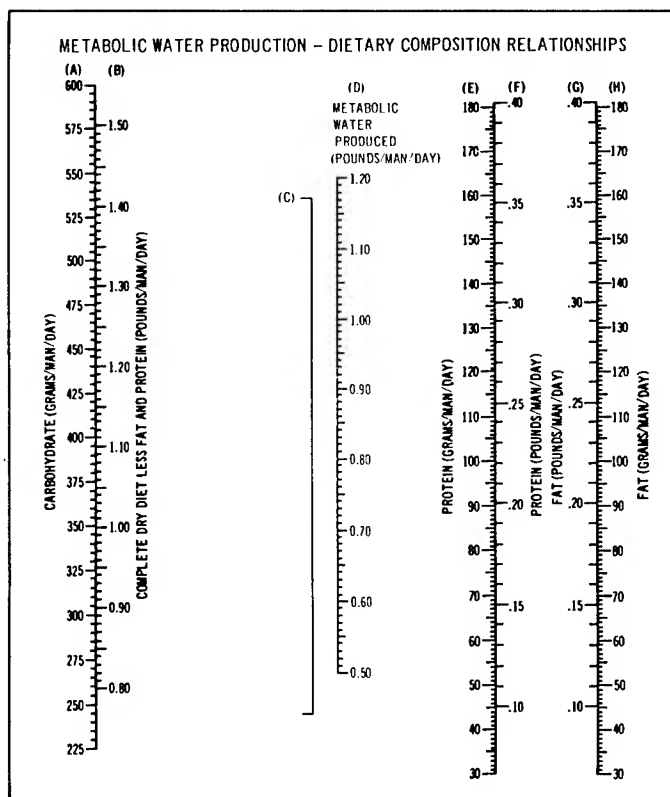


Figure 14-6 (continued)

h.

This figure was designed to determine the relative volume in cubic inches of a complete dry diet when the weight ratios of carbohydrate, fat and protein are known.

EXAMPLES OF USE

Example 1 - What is the daily volume of 2800 Kcal. diet consisting of 530g. of carbohydrate, 44.5g. of fat and 70g. of protein?

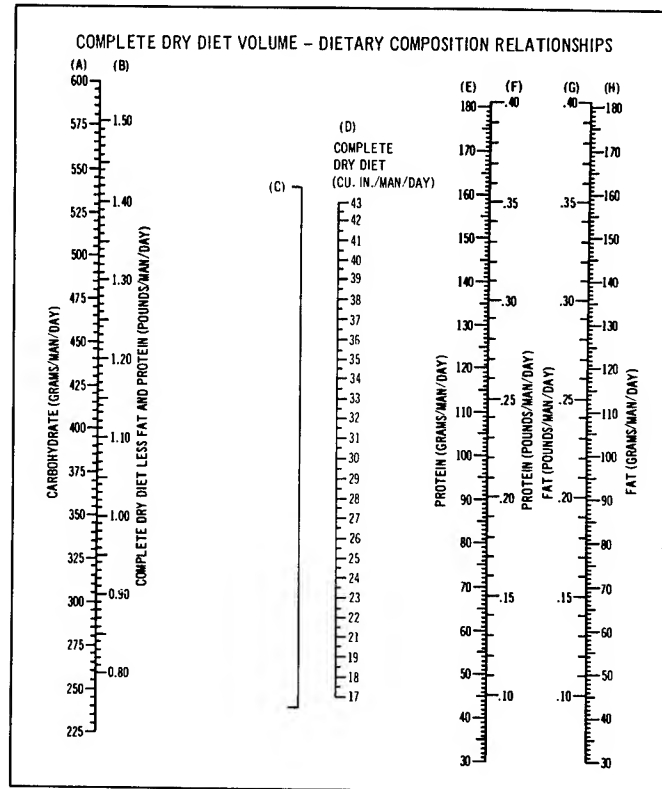
Solution - Draw a straight line from the 530 point on Scale A through the 44.5 point on Scale H. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale E. This line will intersect Scale D to give the desired answer.

Answer - 30.6 cu. in./man/day.

Example 2 - What is the daily volume of a 2600 Kcal. diet consisting of 275g. of carbohydrate, 158g. of fat and 70g. of protein?

Solution - Draw a straight line from the 275 point on Scale A through the 158 point on Scale H. From the intersect formed by this line on Scale C draw a straight line through the 70 point on Scale E. This line will intersect Scale D to give the desired answer.

Answer - 28.5 cu. in./man/day.



i.

This figure was designed to determine the relative density-volume factor, as compared to water, of a complete dry diet when the weight ratios of carbohydrate, fat and protein are known. This density - volume factor divided by the weight of the diet in pounds and multiplied by 62.43 (pounds weight of cubic foot of water) will give the weight per cu. ft. of the diet.

EXAMPLES OF USE

Example 1 - What is the weight in pounds/cu.ft. of a 2800 Kcal. diet consisting of 530g. of carbohydrate, 44.5g. of fat and 70g. of protein?

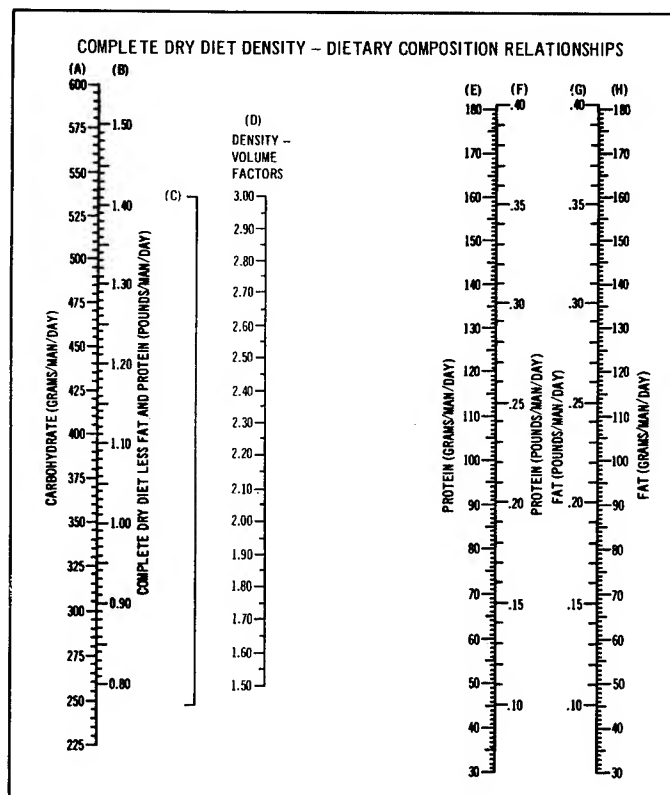
Solution - From Figure 4 the weight of a complete dry diet with this composition is found to be 1.64 pounds. Draw a straight line from 530 point on Scale A (Figure 9) through the 44.5 point on Scale H. From the intersect formed by this line on Scale C draw a straight line through 70 point on Scale E. This line will intersect Scale D to give the desired Density - Volume Factor which in this case is equal to 2.46.

Calculations - $\frac{2.46}{1.64} \times 62.43 = 93.5$ pounds/cu. ft.

Example 2 - What is the weight in pounds/cu.ft. of a 2600 Kcal. diet consisting of 275g. of carbohydrate, 158g. of fat and 70g. of protein?

Solution - Using the same manipulations as described in Example 1, the following values are obtained: diet weight equals 1.34 pounds and the Density - Volume Factor equals 1.84.

Calculations - $\frac{1.84}{1.34} \times 62.43 = 85.6$ pounds/cu. ft.



Operational Considerations of Packing and Dispensing of Foods

The space environment presents several constraints on the design of space food and feeding systems. These are summarized in Tables 12-7a and 12-7b. These foods should be available to crews in a shirt-sleeve environment and in pressure suits during the appropriate phases of the mission. Several types of dispensing devices have been designed (11, 26, 63, 77, 87, 98). Snack items should be readily available (11).

The packaging form must conform to the storage space available (72). It must resist the physical factors of the environment. Crumbling, spilling, and leaking must be kept to a minimum because of the danger of floating particles in the weightless environment (7). In general, the packaging must be operative under the following environmental conditions:

- Temperature range: 0°F to 150°F
- Humidity: up to 90 or 100 percent
- Vacuum: as low as 10^{-4} mm Hg
- Acceleration: up to 10 g

Other factors to consider are: level of chronic vibration; nature of the ambient gas; duration of storage; pH, fat content, microbiology, light sensitivity and consistency of the food, type and level of trace contaminants in the atmosphere, and maximum radiation background.

Figure 14-7
Biological Engineering and Operational Constraints in Space Feeding Systems
(After Heidelbaugh⁽³⁴⁾)

a. Sources of Constraints on Feeding Systems

Biological constraints	Engineering constraints	Operational constraints
Food safety limits	Temperature tolerance	Rehydration time
Acceptability limits	Weight limitation	Handling
Gastroenterologic limits	Volume limitation	Food heating and cooling
Nutritional limits	Water for rehydration	Food residue stabilization
Dietetics	Pressure	Vehicle interface
	Relative humidity	
	Acceleration	
	Vibration	

b. Typical Engineering Constraints on Feeding Systems

Constraint	Specification requirements		
	Zero-g feeder-pack*	Meal-pack**	Feeding system†
Temperature tolerance	0 to 80 F. (-17.8 to 26.7 C.) for 36 hr.	0 to 90 F. (-17.8 to 32.2 C.) for 90 days and 130 F. (54.5 C.) for 3 hr.	0 to 90 F. (-17.8 to 32.2 C.) for 90 days and 130 F. (54.5 C.) for 3 hr.
Weight limitation	Conform to feeding system	Conform to feeding system	1.9 lb./man/day
Volume limitation	Conform to feeding system	Conform to feeding system	225 cu. in./man/day
Water for rehydration	USPHS potable standards	Not applicable	Not applicable
Pressure	29 to 1×10^{-4} mm. Hg	289 to 29 mm. Hg	289 to 29 mm. Hg
Relative humidity	0 to 100% for 36 hr.	0 to 100% for 90 days	0 to 100% for 90 days
Acceleration	Not applicable	1 to 7.25 g in 325 sec.	1 to 7.25 g in 325 sec.
Vibration	Not applicable	5 to 2,000 c.p.s.	5 to 2,000 c.p.s.

*One portion of food vacuum packaged in a zero-g feeding package. **Selected zero-g feeder-packs assembled into a meal unit and vacuum packaged in an overwrap. †Configuration of meal-packs designed to satisfy pilot and flight requirements. C.P.S. = cycles per second.

Figure 14-7 (continued)

c. Microbial Requirements for Foods in Space Feeding Systems*

Category	Required limit
Total aerobic plate count	Not greater than 10,000/Gm.
Total coliform count	Not greater than 10/Gm.
Fecal coliform count	Negative in 0.5 Gm.
Fecal streptococci count	Not greater than 20/Gm.
Coagulase-positive staphylococci	Negative in 0.5 Gm.
Salmonellae	Negative in 5 Gm.

* When examined by the methods suggested by El Bisi (22).

Packaging must have the following functional characteristics:

- Package proportion: ease of handling and use.
- Water of reconstitution: provide for the package to accept water directly from a probe without contaminating the probe and to hold the water and contents without spillage after removal of the probe
- Kneading: provide for kneading of the enclosed contents without spillage and with adequate visibility.
- Food delivery to mouth: provide means on the package for direct transfer of food (or beverage) from package to mouth without loss of contents; provide for neck of package to close after initial opening and between moments of ingestion to prevent loss of contents; provide for delivery to closed pressurized helmet.
- Storage: integration with storage modules and waste disposal
- Package stabilization: provide a means for physical attachment to a surface or to clothing.

The material considerations for packing are:

- Impart no toxicity to food
- Stability in temperature ranges stated
- Low permeability to water vapor and gases
- Ability to withstand Mullen burst of 40 psi
- Flexibility
- Puncture-resistance (from granular type foods) on kneading
- Minimum evaporation rates in vacuum
- Radiation-resistance within anticipated cabin module exposures
- No cracking at low temperature
- No peeling at high temperature
- Sealability
- Transparency

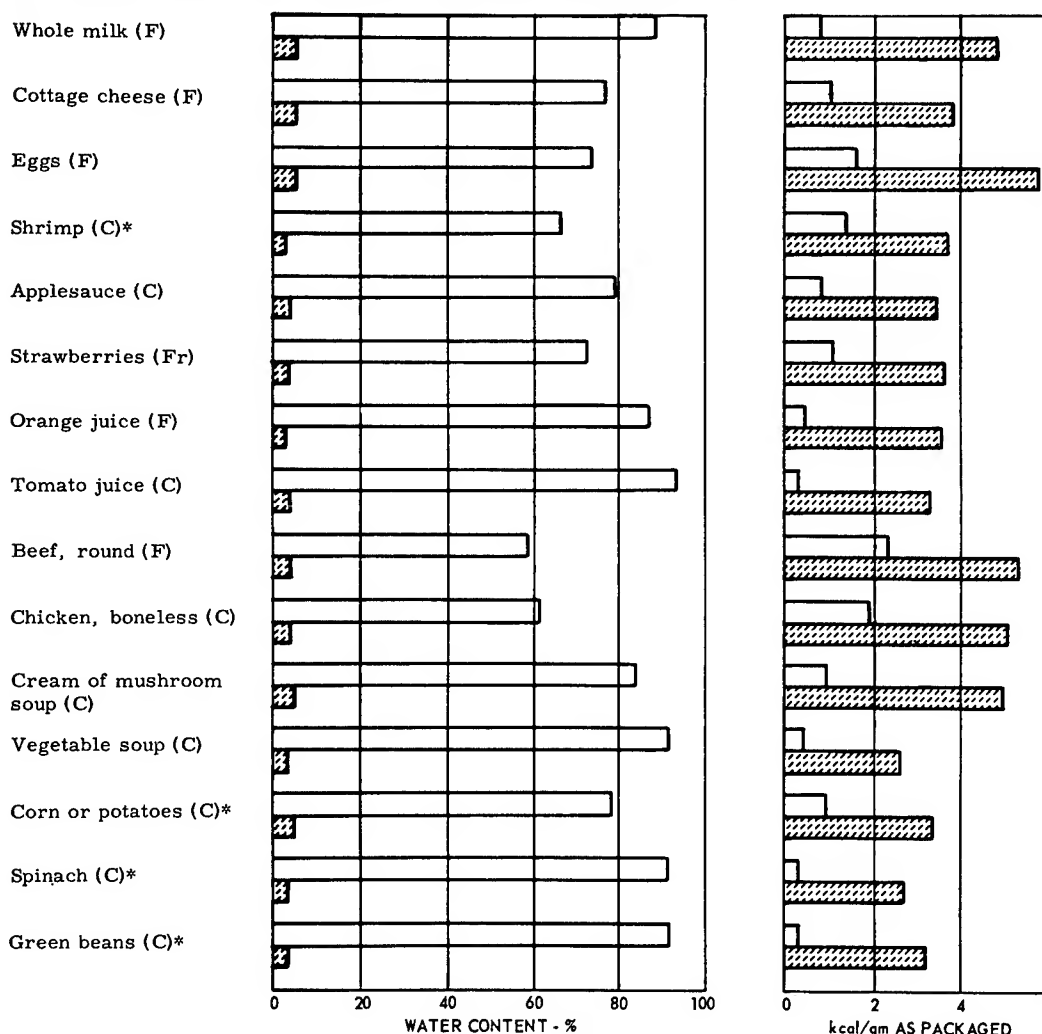
The following discussion illustrates several solutions to the weight, power and secondary constraints imposed by the space environment. Foods of high density can reduce considerably the weight penalty of the nutrition subsystem. The density of foods may be increased by dehydration and compression (53, 100). The effect of dehydrating food is seen in Figure 14-8a in terms of percent of water content attainable and kcal/gm as packaged (96). These are for standard, commercially available, food items.

Density of dehydrated foods may be increased by reducing interstices to a minimum in the food and between packages. This reduction can be

Figure 14-8

Weight Penalties of Foods and Feeding Systems

a. Water Content and Weight of Fresh and Dehydrated Foods



*Data based on drained solids.

□ (F) Fresh, (C) Canned, (FR) Frozen Food
 ▨ Dehydrated Food

(After U.S. Department of Agriculture (96))

Figure 14-8 (continued)

b. Weight, Volume, and Power for Several Types of Feeding Systems (See text)

Feeding System	Food		Environmental Conditions	Equipment			
	Weight	Volume		Type	Weight	Volume	Power
<u>Minimal Acceptability:</u> Foods compressed, freeze dehydrated, and limited in variety; no food service equipment available; temperature of water for food reconstitution 80-90°F.	1.0	0.06	Weightlessness	Water Storage Unit	1.5	0.4	0.01
<u>Moderate Acceptability:</u> A moderate variety of pre-cooked dehydrated foods, instant beverages, and bite-size pieces; approximately half the water at 40°F ± 5°, the remaining half at 180°F ± 10°; food service equipment limited to a water cooler and heater.	1.7	0.13	Weightlessness	Water Heater	5.0	0.6	0.30
				Thermo-Electric Water Cooler	5.5	0.7	0.45
<u>High Level of Acceptability:</u> A moderate variety of pre-cooked dehydrated foods, instant beverages, bite-size solids, and one pre-cooked frozen meal per day; approximately 4/5 of the water requirement for food preparation, the remaining 1/5 contained in frozen foods.	2.5	0.15	Partial Gravity	Water Heater	5.0	0.6	0.30
				Thermo-Electric Water Cooler	5.5	0.7	0.45
				Thermo-Electric Freezer	158	12.0 capacity	15.00
				Oven	10.0	0.9	1.00

(After Brehm⁽¹⁸⁾)

accomplished by compression of foods into block forms that may approach the average molecular density of the products (53,100). However, such a procedure reduces a normal chunk food to a homogeneous paste upon rehydration. Furthermore, rehydration rate is reduced in compressed foods, especially by the constraint of only cold water available (11). (See below Table 14-10c). Several approaches to the problem of retaining the particulate character of the foods are to avoid excessive compression; to avoid freeze-dried foods whenever possible in favor of foods dried by conventional methods; or to shape the foods into blocks within their packages by vacuum-molding.

Caloric density of foods may be increased, independent of physical density, by exchanging low calorie carbohydrates (4 kcal/g) for high calorie fats (9 kcal/g). However, nutritional requirements and palatability are factors that limit the quantity of fat to about 50 percent of the caloric intake. This should be kept in mind when interpreting Figures 14-5 and 14-6.

Table 14-8b represents weight, volume, and power estimates for several types of feeding systems. Food values cited are for one man for one day. A standard value has been assumed for the daily water supply: 2500 cc/man. It

is assumed that the crew size will be two to four men and that mission durations will extend from two weeks to two months. Food weight and volume values include weight of food, dispensers, and packaging. The equipment data are based on state of the art designs. Values for weight, power, and volume of all equipment, except the freezer, will meet the needs of space missions of indefinite duration, provided only two crew members eat at one time. Freezer weight, volume and power data are based on food supplies for a four man crew, 60 day mission and are not applicable to early Apollo mission

Prototype Space Diets and Organoleptic Preferences

Early in the Apollo program an attempt was made to improve on the palatability of the Gemini diet by establishing astronaut preference for space-type food. The diet presented here as a prototype was designed using the general nutritional principles outlined above (11). This particular diet will probably not see operational use in Apollo because it was not designed specifically with the time-temperature criteria for stability in mind (8). A modified Gemini diet is under study for operational use in Apollo (see below). The Stanford Research Institute Study is being presented because it represents a detailed compositional and hedonic study (with astronaut preferences) of a diet which could be modified for extended space use. The data elucidates some of the problems which future designers of space diets should consider.

The approximate composition of items developed for this diet is listed in Table 14-9. The formulated items were analyzed by the Association of Official Agricultural Chemists (AOAC) methods. Standard and uniform products were computed from USDA Handbook No. 8 (59). (Addresses of food sources are available on p. 133 of Reference (11). Evaluation of acceptability of these items in several menu forms is available (10, 11).

The general food preference of astronauts and other test subjects for the types of food presented in Table 14-9a are seen in Table 14-9b. The variability in evaluation by non-astronaut subjects of the items in prototype diet of Figure 14-9a is seen in Table 14-9c. The data were obtained in open laboratory conditions with no attempt at cabin or work simulation. The cycling pattern of the diet as well as monotony and fatigue factors involved over a 14-day feeding period must be considered (80, 83). More detailed data are available for three different menu cycles of these foods with some variation in presentation of different items. The types of snacks suggested for prototype space diets are seen in Table 14-10a. Table 14-10c evaluates the rehydration characteristics of these snacks. Subjective evaluation of these snacks under open laboratory conditions is seen in Table 14-10b. Details regarding the unsatisfactory nature of some of the snacks are available (11). It is clear that a larger sampling of opinion is required for definitive evaluation of the suitability of these dietary components in space diets of long duration.

Other precooked, dehydrated, compressed and liquid diets have also been evaluated for long periods in space-cabin simulators (21, 37, 41, 44, 45, 46, 51, 56, 73, 82, 86, 88, 99). These references cover both preparation and study of the diets.

Figure 14-9

Composition and Astronaut Preferences for Components
of a Prototype Space Diet(After Calloway et al⁽¹¹⁾)

a. Approximate Composition of a Prototype Space Diet

Food Item	Source ¹	Quantity (g per 100 g) ²					
		Moisture	Ash	Nitrogen	Crude Fat	Crude Fiber	Carbohydrate (by difference)
Almonds, blanched	White's	(4.7)	(3.0)	(2.98)	(54.1)	(2.7)	(16.9)
Applesauce	Vacu Dry	(2.0)	(1.8)	(0.29)	(tr)	(4.9)	(89.4)
Apple mincemeat pudding (a)	SRI Formula	19.6	2.7	0.48	18.8	2.2	53.7
Apple mincemeat pudding (b)	SRI Formula	(5.0)	(3.2)	(0.57)	(22.3)	(2.6)	(63.3)
Apricots	Mariani	30.6	2.5	0.55	0.3	2.3	60.9
Bacon bar	Wilson	15.9	8.1	6.08	35.9	0.5	1.6
Beaten biscuit	Merritt's	3.8	2.4	1.30	17.0	0.9	68.4
Beef with potatoes and gravy	SRI Formula	3.0	6.3	6.00	7.1	0.8	45.3
Beef with spaghetti and tomato sauce (b)	SRI Formula	2.3	6.7	4.46	19.3	1.0	42.8
Beef sticks	Bob Ostrow	12.6	6.0	4.50	48.8	1.0	3.5
Bread pudding	SRI Formula	2.0	2.6	0.79	17.8	1.2	71.4
Brownies	Langendorf	7.6	1.0	0.81	21.7	1.2	63.5
"Buttered" cinnamon roll	SRI Formula	(12.3)	(0.9)	(1.03)	(20.2)	(0.9)	(59.5)
"Buttered" rye	Wedemeyer	37.2	2.3	1.70	tr	0.6	50.2
Candy-coated chocolate	Boldemann	1.0	2.7	0.98	18.2	1.1	71.0
Caramels	Calliard and Bowser	(7.0)	(1.0)	(0.46)	(11.6)	(0)	(77.5)
Cashews	Circus	(3.6)	(2.7)	(2.96)	(48.2)	(1.3)	(25.7)
Cereal with apples in sauce	SRI Formula	1.3	2.1	1.07	17.9	1.4	71.2
Chicken with potatoes and gravy (b)	SRI Formula	3.5	6.1	4.16	18.7	1.1	44.6
Chicken salad	SRI Formula	2.0	2.8	4.74	26.8	1.2	37.6
Chicken soup	SRI Formula	1.2	6.7	7.38	29.9	0.3	15.8
Chili con carne with crackers	SRI Formula	3.6	6.6	4.26	21.2	1.1	40.9
Chocolate bar	Hershey	(1.1)	(1.7)	(0.96)	(33.5)	(0.5)	(55.2)
Chocolate with almonds bar	Hershey	(0.6)	(1.8)	(1.28)	(38.6)	(0.6)	(49.4)
Cinnamon roll	Svenhard	13.3	1.0	1.12	13.8	0.9	64.5
Coffee	Freeze Dry	(2.6)	(9.7)	(2.80)	(tr)	(tr)	(35.0)
Cocoa (a)	SRI Formula	1.4	4.4	2.75	1.9	1.3	73.8
Cocoa (b)	SRI Formula	(2.3)	(4.1)	(2.51)	(6.8)	(1.0)	(70.1)
Coconut macaroons	Archway	8.8	1.0	0.67	16.5	2.9	66.6
Crab Newburg with toast	SRI Formula	2.0	4.9	7.41	37.1	0.3	9.4
Cream, synthetic	Carnation	(5.8)	(3.2)	(1.50)	(27.5)	(0)	(54.1)
Crisp cereal with peaches	SRI Formula	2.7	2.2	0.74	26.8	0.6	63.1
Custard with fruit	SRI Formula	1.6	3.1	1.76	1.6	1.6	80.9
Fish wafers	Freeze Dry	1.1	5.9	9.28	18.9	0.3	15.8
Fruit cake	Cross & Blackwell	(18.1)	(2.1)	(0.77)	(15.3)	(0.6)	(59.1)
Grape drink	Wylar	(0.1)	(0.4)	(0.02)	(0.2)	(0.2)	(99.0)
Grapefruit drink	General Foods	(0.1)	(0.4)	(0.02)	(0.2)	(0.2)	(99.0)
Grapefruit juice	SRI Formula	(0.8)	(2.3)	(0.61)	(0.8)	(0.3)	(92.0)
Ham chunks	Freeze Dry	0.4	7.3	5.58	35.0	0.2	22.2
Ham in mustard sauce	SRI Formula	1.2	4.6	3.15	50.7	0.2	23.6
Honey nut roll	Istanbul Bakery	10.8	1.4	1.29	29.3	2.3	48.2
Lemon drink	Wylar	0.1	0.4	0.02	0.2	0.2	99.0
Lemon-apricot pudding (a)	SRI Formula	1.8	4.8	1.40	0.5	0.5	83.6
Lemon-apricot pudding (b)	SRI Formula	(3.1)	(4.3)	(1.43)	(9.2)	(3.4)	(74.0)
Margarine, anhydrous	Coldbrook	0.4	0.1	0.01	99.1	0	0
Mints	Norcal	(1.0)	(0)	(0)	(0)	(0)	(99.0)
Orange drink	General Foods	(0.1)	(0.4)	(0.02)	(0.2)	(0.2)	(99.0)
Orange juice	Plant Industries	(1.0)	(3.4)	(0.8)	(1.7)	(0.8)	(88.1)
Pea soup with bacon	SRI Formula	4.4	9.5	5.15	29.2	0.56	24.1
Pea soup	Vacu Dry	3.6	9.3	4.99	10.0	1.5	44.4
Petit fours	Continental	3.6	1.0	2.37	31.2	0.9	48.5
Pineapple juice	Patterson	1.5	2.0	0.55	0.2	0.1	92.8
Potato soup	SRI Formula	2.2	4.6	0.68	32.9	1.3	54.6
Potatoes with bacon	SRI Formula	11.0	5.1	3.04	31.5	1.3	32.1
Potatoes with "butter"	SRI Formula	2.5	4.6	0.68	37.8	0.9	49.9
Pumpnickel	Juillard Fancy Foods	26.9	1.1	1.04	0.8	1.4	63.9
Salami	Gallo	21.9	5.8	4.37	37.4	0.2	7.4
Seafood with noodles Orientale	SRI Formula	2.0	4.2	5.98	36.7	0.9	18.8
Spanish rice	SRI Formula	0.6	3.9	2.29	36.8	1.0	43.4
Starch jelly candy	Charm	(11.7)	(0.1)	(tr)	(0.7)	(0)	(87.4)
Swedish meatballs	SRI Formula	1.6	4.1	3.57	42.1	0.6	29.3
Tea	Lipton	(3.8)	(6.1)	(5.0)	(tr)	(0.1)	(80.0)
Tomato soup	SRI Formula	2.2	5.0	1.17	38.5	1.9	45.1
Wheat bits with raisins	SRI Formula	4.9	2.2	0.76	14.4	1.0	72.8
Yams with bacon and apples	SRI Formula	5.2	5.3	2.53	14.5	1.6	57.6

¹ Manufacturer of conventional items or SRI-developed formula² Values in parentheses are from USDA Handbook No. 8; others are by analysis.

Table 14-9 (continued)

- b. Mean Food Preference Scores of Astronauts and of Other Test Subjects. Ratings are based on same hedonic scale as Table c.

Item	Rating	
	Astronauts ¹	Other Test Subjects ²
Almonds	5.3	5.1
Apples	5.6	5.1
Apricots	6.0	3.9
Asparagus	5.3	4.2
Bacon	5.6	5.7
Bananas	5.3	5.2
Beef	6.0	5.6
Butterscotch flavor	5.1	3.9
Candy	5.1	4.4
Carrots	4.9	4.7
Celery	5.5	5.3
Cereal, cold	5.0	4.2
Cereal, hot	5.0	5.5
Chicken	5.1	3.9
Cheese	4.9	5.1
Chocolate flavor	5.9	5.3
Coconut	4.5	4.4
Codfish	3.8	1.5
Coffee	4.8	4.7
Crab	5.8	3.5
Dates	5.4	3.0
Eggs	5.4	5.6
Fish	4.9	3.7
Grapefruit	5.5	5.0
Ham	5.3	5.0
Jelly, jam	5.1	4.5
Lemons	5.3	4.8
Liver	4.8	3.5
Lobster	5.9	4.1
Luncheon meat	4.4	4.9
Onions	5.1	5.1
Oranges	5.8	5.2
Peaches	5.9	5.3
Peanuts	5.4	5.1
Peas	4.5	5.0
Pineapple	5.5	4.4
Potatoes	4.9	5.1
Pudding	4.3	3.9
Raisins	5.3	4.2
Rice	5.1	4.3
Sausage	5.5	5.2
Shrimp	5.8	4.5
Squash	4.4	2.3
Strawberries	5.8	5.7
Sweet potatoes	4.5	3.8
Tea	5.3	5.0
Tomatoes	5.9	4.8
Turkey	5.1	4.9
Vanilla flavor	5.5	4.8
Yams	5.0	2.6

¹ Armstrong, Glenn, Grissom, McDivitt, Schirra, Slayton, Stafford, and Young

² Eleven subjects tested prior to habitability studies.

Table 14-9 (continued)

c. Mean Evaluations Scores¹ Assigned to Meal Items of a Prototype Space Diet by Subjects in Habitability Study

Item	Rating ²	
Main Dish		
Seafood with noodles Orientale	6.0	
Beef with spaghetti	5.3	(5.6) ³
Chili con carne	5.0	
Crab Newburg	4.7	
Chicken with potatoes and gravy	4.5	
Chicken salad	4.0	(3.0)
Potatoes with "butter"	3.8	
Swedish meatballs	3.5	
Ham with mustard sauce	2.6	
Beef with potatoes and gravy		(2.6)
Soup		
Chicken		(4.0)
Potato	3.7	
Tomato	3.0	
Beverage		
Orange juice	6.0	(6.0)
Cocoa	5.6	(5.6)
Lemon drink	5.4	(5.6)
Grape drink	5.3	
Tea	5.2	
Coffee	5.0	(3.3)
Grapefruit juice	5.0	
Pineapple juice		(3.7)
Dessert		
Custard with fruit	5.0	
Apple mincemeat pudding	4.8	
Lemon pudding	4.8	
Bread pudding	4.5	
Breakfast		
Crisp cereal with peaches	5.2	
Cereal with apples	5.0	(3.6)
Wheat bits with raisins	4.8	
Potatoes with bacon	4.8	
Yams with bacon and apples		(3.3)
Snacks		
Chocolate with almonds bar	6.0	(6.0)
Chocolate bar		(6.0)
Cashews	5.3	
Coconut macaroons	5.3	
Mints	5.3	(5.0)
Cinnamon roll	5.0	
Beef sticks	5.0	
Petit fours	5.0	
Fruit cake	5.0	
Brownies	4.8	
Bacon bar	4.6	
Honey nut roll	4.4	
Apricots	4.0	(4.6)
"Buttered" rye	4.0	(2.3)
Ham chunks	3.8	
Caramels	3.7	
Starch jelly candy	3.7	(5.7)
Fish wafers	2.6	
Rye with salami		(2.6)

1. Numerical values were assigned based on a hedonic scale, with 6 as "Like very much" and 0 as "Dislike very much".
2. Each value represents the average of 3 to 6 judgements.
3. Ratings in parentheses were assigned in a previous experiment.

Table 14-10
Evaluation of Snacks in a Prototype Space Diet

(After Calloway et al⁽¹¹⁾)

a. Snacks Prepared for a Prototype Space Diet

Item	Description	Supplier	Weight (g)	Treatment
Almonds	Blanched, whole	White's	50	None
Apricots	Dried halves	Mariani	29	None
Bacon	Compressed	Wilson	53	Crumbled and recompressed
Bacon bar	Compressed	Wilson	85	None
Beef sticks	Dried	Bob Ostrow	56	None
Beaten biscuit	Rounds, 3/4-inch diam	Merritt's	15	None
Brownies	Cakes, top-frosted	Langendorf	78	None
"Buttered" cinnamon roll	Squares, 3/4-inch Anhydrous margarine	Svenhard Coldbrook	85 7	Cinnamon roll compressed; coated with anhydrous margarine
"Buttered" pumpernickel	Rounds, 1 1/2-inch diam Anhydrous margarine	Juillard Fancy Foods Coldbrook	40 8	Rounds spread with anhydrous margarine
"Buttered" pumpernickel with sausage	Rounds, 1 1/2-inch diam Anhydrous margarine Sliced salami	Juillard Fancy Foods Coldbrook Gallo	40 24 8	Salami sandwiched between 2 slices spread with anhydrous margarine
"Buttered" rye	Squares, 3/4-inch, "Vollkornbrot" Anhydrous margarine	Wedemeyer Coldbrook	100 20	Squares spread with anhydrous margarine
Candy-coated chocolate	Rounds, 9/16-inch diam	Boldemann	60	None
Caramels	Bars, 2-inch x 1/2-inch	Caillard and Bowser	55	None
Cashews	Roasted	Circus	57	None
Chocolate	Bar	Hershey	57	None
Chocolate with almonds	Bar	Hershey	57	None
Cinnamon roll	Sliced	Svenhard	57	None
Coconut macaroons	Pieces, 1 1/2-inch x 3/4-inch	Archway	80	None
Fish cakes	Rounds, freeze-dried	Freeze Dry	45	Packaged under N ₂
Fruit cake	Bar	Cross & Blackwell	57	None
Ham chunks	Squares 3/4-inch freeze-dried	Freeze Dry	28	Packaged under N ₂
Honey nut roll	Pieces	Istanbul Bakery	57	None
Mints	Rounds	Norcal	30	None
Petit fours	Coated square cakes	Continental	60	None
Starch jelly candy	Pieces, 1 1/2-inch x 3/4-inch	Charm	76	None

Table 14-10 (continued)

b. Results of Subjective Evaluation of Snack Items
in a Prototype Space Diet After Storage Tests

(Two weeks at 100°F; 90% relative humidity; vacuum 10^{-1} mm)

Item	Rating			Comments
	Acceptable	Improvement Needed	Unacceptable	
Candy mints	x			
Dried apricots	x			
Beef sticks	x			
Candy-coated chocolate	x			
Toffee fingers	x			
Beaten biscuits	x			
Almonds, blanched unsalted	x			
Peanuts, bland coating	x			
Caramels	x			
Macaroons	x			
Starch jelly candy		x		Eliminate sugar coating
Fruit cake		x		Coating necessary to avoid crumbling
Rye bread with butter		x		Coating necessary to avoid crumbling
Bacon bar	x			
Candy-coated almonds			x	Coating crumbles
Cashews		x		Eliminate salt
Brownies			x	Crumbles and melts
Chocolate (high melting point)			x	Melts
Ham chunks			x	Excessive crumbling
Fish wafers			x	Excessive crumbling
Petit fours			x	Melts
Honey nut roll			x	Crumbles; too sticky
Cinnamon roll		x		Coating necessary to avoid crumbling

Table 14-10 (continued)

c. Rehydration of Prototype Dehydrated Space Foods in Cold Water (80°F)

Item	Rating after 2 minutes			
	Good	Fair	Poor	Comments
Applesauce ¹	x			
Potatoes with bacon		x		
Crab Newburg with toast	x			
Bread pudding	x			
Crisp cereal with peaches ¹	x			
Ham in mustard sauce			x	
Apple mincemeat pudding	x			
Wheat bits with raisins ¹	x			
Beef with spaghetti and tomatoes	x			Noodles still crisp
Cereal with apples in sauce	x			
Chicken salad		x		Slight starchy taste
Lemon pudding ¹	x			
Swedish meatballs			x	
Chili con carne with crackers	x			Meat "crunchy"
Custard with fruit	x			
Chicken with potatoes and gravy	x			Flavor not as good
Seafood with noodles Orientale	x			
Pea soup			x	
Tomato soup			x	
Potato soup			x	
Spanish rice	x			
Cocoa	x			Must be vigorously shaken
Coffee	x			
Orange juice ¹	x			
Grapefruit juice ¹	x			
Lemon drink ¹	x			
Grape drink ¹	x			
Potatoes with "butter"			x	

¹Normally rehydrated with cold water.

Apollo foods are currently of two types - nominal and contingency (45, 46). Table 14-11 covers the nutrient composition and Table 14-12 the meal and cycle form of the Apollo nominal mission diet. Table 14-13a covers the nutrient composition of semisolid and rod form of the contingency diet. The semisolid foods can be made up in foil packs or in tube form, the latter eaten by being squeezed through an aluminum toothpaste tube. Tubed foods are squeezed through an aperture in the helmet of a space suit. The rod form are in long spaghetti cylinders, 13 feet of which supply the normal daily requirement per man. The rod food is forced by a plunger through an aluminum tube screwed into an aperture in the helmet. In a recent study, four human male subjects participated in a 90-day experiment consisting of 60-day and 30-day confinement periods with a 5-day break between. The subjects were confined either to the controlled activity facility or the chamber of the Life Support Systems Evaluator at the Aerospace Medical Research Laboratories, Wright-Patterson AFB (45). In the chamber, they were in 50% oxygen-50% nitrogen at 382 ±2.6 mm Hg, wearing pressure suits unpressurized and pressurized at 3.7 psi. The subjects ate a fresh food diet, An Apollo nominal diet, or an Apollo contingency diet that provided 2200, 2500, and 900 kcal/day, respectively. The rod form of the contingency diet was the more accept-

Table 14-11

Nutrient Composition of Test Apollo Nominal Mission Diet

(After Katchman et al⁽⁴⁵⁾)

Constituent	Units	Cycle I	Cycle II	Cycle III	Cycle IV
Weight	g	544.50	543.10	541.20	545.45
Water	g	16.1	16.3	10.4	15.0
Calories	cal	2622	2650	2601	2637
Protein	g	102.9	112.7	109.7	107.1
Fat	g	118.8	125.6	111.5	122.5
Carbohydrate	g	287.2	269.5	289.9	290.3
Fiber	g	4.31	3.62	6.65	4.32
Ash	g	19.7	19.4	19.6	20.6
Calcium	mg	993	531	866	810
Phosphorus	mg	1618	1443	1381	1751
Iron	mg	11.4	10.6	9.7	11.1
Sodium	mg	4025	7076	4513	4833
Potassium	mg	2474	2411	2059	2208
Magnesium	mg	267.0	251.0	220.5	255.4
Chloride as NaCl	g	10.34	10.13	11.19	11.79

Analysis of the Apollo nominal mission diet was supplied by the Food Division, U. S. Army Natick Laboratories, Natick, Massachusetts.

Table 14-12

Menu of Test Metabolic Diets for Apollo Mission

(After Katchman et al⁽⁴⁵⁾)

Meal A	Meal B	Meal C	Meal D
<u>Fresh food diet</u>			
Canadian bacon Bread and butter Applesauce Gingerbread Chocolate milk	Roast beef sandwich Sliced peaches Peanut butter cookies (3) Grapefruit Tang	Sliced turkey Dinner rolls (2) Apricot halves Pound cake Milk	Ham and cheese sandwich Red cherries Brownie Orange Tang
<u>Apollo nominal mission diet</u>			
<u>Cycle I</u>			
Toasted oat cereal Sausage bites Toasted bread cubes Orange drink	Beef and gravy Corn bar Date fruitcake Toasted bread cubes Tea and sugar	Pea soup Salmon salad Cinnamon toast Fruit cocktail Orange drink	Chicken sandwich Chocolate pudding Peanut cubes Orange-grapefruit drink
<u>Cycle II</u>			
Apricot cereal cubes Canadian bacon and applesauce Toasted bread cubes Cocoa	Beef bites Potato salad Pineapple fruitcake Orange drink	Beef sandwich Chicken salad Peach bar Banana pudding	Potato soup Chicken and gravy Toasted bread cubes Peanut cubes Tea and sugar
<u>Cycle III</u>			
Sugar coated flakes Sausage patties Cinnamon toast Orange-grapefruit drink	Tuna salad Cheese sandwich Apricot pudding Orange drink	Beef pot roast Pea bar Toasted bread cubes Pineapple cubes Tea and sugar	Crab bites Cinnamon toast Applesauce Brownie Grapefruit drink
<u>Cycle IV</u>			
Strawberry cereal cubes Bacon squares Beef sandwich Orange drink	Corn chowder Beef sandwich Chocolate pudding Gingerbread	Shrimp cocktail Chicken and vegetables Toasted bread cubes Butterscotch pudding Orange-grapefruit drink	Beef and vegetables Spaghetti and meat sauce Cinnamon toast Apricot cubes Tea and sugar

Table 14-13

Nutrient and Chemical Composition of Test Contingency Diet for Apollo Mission *

(After Katchman et al⁽⁴⁵⁾)

a.

Constituent	Units	Semisolid	Rods
Energy per unit	kcal	475.0	485.0
Weight per unit	g	140.0	110.0
Energy per gram of diet	kcal	3.4	4.4
Carbohydrate	g	65.3	72.1
Protein	g	11.9	10.0
Fat	g	18.5	17.5
Water (by difference)	g	44.0	10.0
Thiamine	mg	2.0	**
Niacin	mg	10.0	**
Vitamin B ₆	mg	0.8	**
Riboflavin	mg	2.0	**
Calcium pantothenic acid	mg	3.0	**

* Analysis of the contingency diet was supplied by the Food Division, U.S. Army Natick Laboratories, Natick, Massachusetts.

** Vitamins are presumed to be present in the rod food in the same amounts as in the semisolid food.

Table 14-13 (continued)

b.

Constituents /24 hr	Units	Foil pack (A)	Rods (B)**	Tube pack (C)	Rods (D)
Dry solids	g	202	196	221	191
Water	g	78	36	116	23
Protein	g	22	28	25	26
Fat	g	38	38	34	36
Carbohydrate (by difference)	g	137	127	159	127
Fiber	g	2	1	1	1
Ash	g	3	3	4	1
Calcium	mg	615	540	510	540
Phosphorus	mg	615	147	570	170
Sodium	mg	285	730	240	120
Potassium	mg	730	258	680	300
Chloride	mg	417	1620	480	370
Magnesium	mg	105	49	74	47

* Analyzed by Wisconsin Alumni Research Foundation, Madison, Wisconsin.

** 2.0 g of sodium chloride added.

able from an organoleptic standpoint. Table 14-14a covers the acceptability ratings of the diets. The tube form was more easily handled from a functional standpoint, although the formulation of the tube food as well as the tube itself needs to be improved to make it operationally more effective than at present. The subjects lost about 500 g/day of body weight while on the contingency diet of which about 50% is estimated to be water. About 40 g/day of body weight was lost because of protein catabolism but no ketone bodies were found in the urine. Blood levels of sodium, potassium, phosphorus, chloride, calcium, and magnesium were maintained in the normal range of clinical values. Physiologic measurements all were in the normal range of clinical values. However, the 17-hydroxycorticoids of the urine decreased to low normal and below normal ranges of clinical values. Three of the four subjects completed a simulated Apollo emergency mission wearing a pressure suit pressurized at 3.7 psi and on a 900-calorie contingency diet. There were no adverse effects upon their health and no evidence that their capacity to function in a normal manner was in any way impaired. Water consumed varied from 700 to 2000 ml/day. Table 14-14b covers the waste management associated with the diets.

Rehydration of Foods

Hot water for rehydration of space foods and the preparation of hot meals represents an important power requirement for the command module during a mission. Since power consumption is a direct function of water temperature above ambient temperature, criteria to aid in the determination of minimum temperature requirements for the rehydration of hot meals are necessary. Operations in the Apollo LEM, for example, require that foods be rehydrated with cold water. Table 14-10c represents rating of prototype space foods after 2 minutes of rehydration in cold water at 80°F.

The subjective nature of palatability as it relates to food temperature is a complex subject that may best be solved by the astronauts themselves. However, a panel composed of a laboratory staff placed the lower temperature of acceptability of semisolid hot foods at 105°F, soup at 115°F, and coffee or tea at 120°F (11). In establishing the water temperature requirements for initiating the hydration of specific foods so that these minimal temperatures are attained, the following data are required:

- cooling rate of food and water mixtures
- temperature drop from mixing food and water without heat loss (at time zero)
- time required for consumption of food

Solution of appropriate cooling-rate equations indicates that the initial water temperature required to have semisolid foods at 110°F ten minutes after rehydration in ambient temperatures of 70°F is 146°F. Under similar conditions, the water temperature required to have coffee at 120°F five minutes after hydration is 145°F. Therefore, maximum initial temperature of hydration water for most foods can be set at 145°F without effects on palatability.

Table 14-14
Organoleptic and Waste Management Evaluation of Nominal
and Contingency Apollo Diets (See text for description)

(After Katchman et al⁽⁴⁵⁾)

a. Organoleptic Evaluation of Different Forms of Nominal and Contingency Apollo Diets

	Apollo nominal mission diet				
	cycle I	cycle II	cycle III	cycle IV	cycle I
Chamber ANM (A)	5.6	6.4	6.5	5.8	6.5
CAF - Chamber ANM (B)	5.6	5.9	6.2	6.2	6.3
	5.7	5.7	6.1	5.9	6.5
CAF - Chamber ANM (B)	6.5	6.8	6.0	6.0	6.2

Test period and condition	Contingency diet					Average per 5-day test period
	day 1	day 2	day 3	day 4	day 5	
CAF Foil pack (A)	1.9	2.4	2.6	2.6	2.0	2.3 ± 0.4
CAF Rods (B)	3.9	4.2	4.1	4.0	3.2	
Chamber Rods (B)	4.2	5.8	5.8	6.0	5.0	
Tube pack (C)	6.0	5.0	4.8	4.3	4.3	

A, B, and C refer to specific versions of diets tested.

CAF = Controlled Activity Facility

Chamber = Life Support Systems Simulator (50% N₂ - 50% O₂ at 382 mm Hg).

Numbers are averages of 4 subjects on a 9 point hedonic scale.

Table 14-14 (continued)

b. Waste Management Nominal Mission and Contingency Diets in Apollo

	Fresh food	Apollo nominal mission food	Contingency food
	<u>Intake, g/24 hr</u>		
Dietary solids	512	568	202
Dietary water	1167	20	89
Ad libitum water	1400 ± 417	2000 ± 182	1500 ± 311
Metabolic water	314	357	134*
	<hr/> 3400	<hr/> 2900	<hr/> 1900
	<u>Excretion, g/24 hr</u>		
Urine	1300 ± 590	1300 ± 580	1100 ± 465
Feces	65 ± 17	86 ± 2.5	32 ± 12
Insensible water	1500 ± 274	1000 ± 68	600 ± 189*
	<hr/> 2900	<hr/> 2400	<hr/> 1700

* Does not include water of metabolism from body stores.

Current Packaging Materials

The operational requirements for food packaging and dispensing have been covered above. Material requirements for use in packaging of space food should ideally meet the criteria posed above. The most stringent requirements are high strength and excellent barrier against penetration by oxygen and water vapor. Tables 14-15, 14-16, and 14-17 represent the physical properties of candidate materials. More detailed analysis of properties of materials in Tables 14-16 and 14-17 are available (11).

Of the single-film materials, fluorohalocarbons such as Aclar have the best water vapor barriers and polyvinylidene chlorides (Saran), the lowest oxygen permeability. Polyethylene is quite permeable to oxygen but is most sealable by heat. All are stable and flexible within the temperature and atmospheric ranges specified. All have good tensile and tearing strength and are puncture resistant. The latter is important because some foods have sharp particles and evacuation of the package required to reduce bloating upon decompression creates high concentrated stresses in the film material. To obtain the best all-around physical properties, various thicknesses of several different film materials are usually laminated together by either extrusion or adhesion. Approximate properties can be estimated by adding the separate properties of each part of the laminate. Actual properties can be obtained only by testing each complete laminate, as the techniques of each converter will cause variances.

Preliminary testing of laminates suggests that the most useful laminate would probably consist of the following individual films (11): Aclar; polypropylene with a Saran coat or Mylar with a Saran coat; and polyethylene (medium density) or Surlyn A (a modified polyethylene).

Metal foil laminates form ideal barriers but are susceptible to damage under folding and kneading, and evacuation. They are also opaque and do not allow visualization of the food during kneading in rehydration. They appear especially useful in package overwraps for grouping daily diets for each man. The most promising foil laminates are (11);

May Industries/Reynolds Aluminum. 2-mil laminate

Mylar	.0005
Aluminum Foil	.0004
Rislan (Nylon 11)	.001

Dow Chemical Co. 3.7-mil laminate

Polypropylene	} individual thicknesses not known
Aluminum foil	
Polyethylene	

Minnesota Mining and Manufacturing Co.

25A20	2.5-mil laminate	} individual thicknesses not known
45AX88	4.5-mil laminate	
Metallized aluminum		
Mylar		
Polyethylene		

Characteristics	Polytri- fluorochloro ethylene (Aclar 33-C)	Polyester (Mylar)	Polyamide (Nylon)	Polyethyl- ene, low density (Marlex)	Vinyl- idene chloride (Saran)	Poly- vinyl chloride (Plivoc)
Weight (in ² /lb)	13,000	20,000	24,000	30,000	16,000- 23,000	20,000- 23,000
Tensile strength* (lb/in of width)	5-6	23-40	9	1.3-2.5	8-20	1.4-5.6
Elongation* (%)	35	35-100	orients	200-800	20-140	150-500
Burst strength; Mullen Test** (points)	35	45-60	-	-	23-35	20
Tear strength; Elmendorf Test*** (grams)	200-350	10-27	-	100-300	10-100	60-1400
Moisture vapor transmission rate (gm mil/day, 100 in ² , atm)	0.4 (at 100°F)	24 (at 103°F)	300-320 (at 100°F)	7-15 (at 77°F)	3 (at 100°F)	70-170 (at 100°F)
Permeability to oxygen cc(STP) mil/day, 100 in ² , atm.	7 (at 75°F)	1.1 (at 70°F and 0% RH)	2.6 (at 73°F and 0% RH)	750	1.0 (at 73°F)	625

Table 14-15

Plastic Films for Food Packaging
(1 mil thick)

(Adapted by Finkelstein⁽²⁵⁾ from
data of Modern Plastics Encyclo-
pedia⁽⁶⁵⁾, Allied Chemical⁽¹⁾, and
Clauser⁽¹²⁾)

*Tensile strength and elongation: American Society of Testing Materials D-882, Procedure 3.

**Mullen Test: American Society of Testing Materials D-774.

***Elmendorf Test: Figures represent pull to continue tear after starting.

Note: The names Aclar, Mylar, Marlex, Saran, and Plivoc are registered trademarks.

Table 14-16

Water Vapor and Oxygen Transmission for Single Films

Film	Operating Temperature (°F)	Water Vapor (per mil thickness) g/100 sq in./24 hr at 100°F and 95% RH	Oxygen (per mil thickness) cc/100 sq in./ 24 hr/atm
Aclar	-420° to 370°	0.015	6-8
Mylar	-80° to 300°	1.8	3-5
Nylon 6	-100° to 300°	36	8
Polyethylene (med. dens.)	-60° to 200°	0.5-5.0	250-400
Saran 7	0 to 250°	0.2-0.3	0.9-1.0
Surlyn A	-160° to 160°	1.5	500

(After Calloway et al⁽¹¹⁾)

Table 14-17

Permeability Data on Laminated Materials

Laminate	Water Vapor g/100 sq in./24 hr at 95% RH	Oxygen cc/100 sq in./24 hr/atm
Milprint, M-Mylar/Polyethylene	0.3-0.5	0.55-0.7
3M 25A6 Mylar/Polyethylene	0.4	7
3M 45A27 Mylar/Polyethylene	0.2	3
RAP-7700 Aclar/Mylar/ Polyethylene	0.03-0.04	2.3

(After Calloway et al⁽¹¹⁾)

Prototype food storage and dispensing bags for Apollo have been designed under the packaging criteria presented above (11). A prototype rehydrating system is also available.

Starvation and Performance Capacity

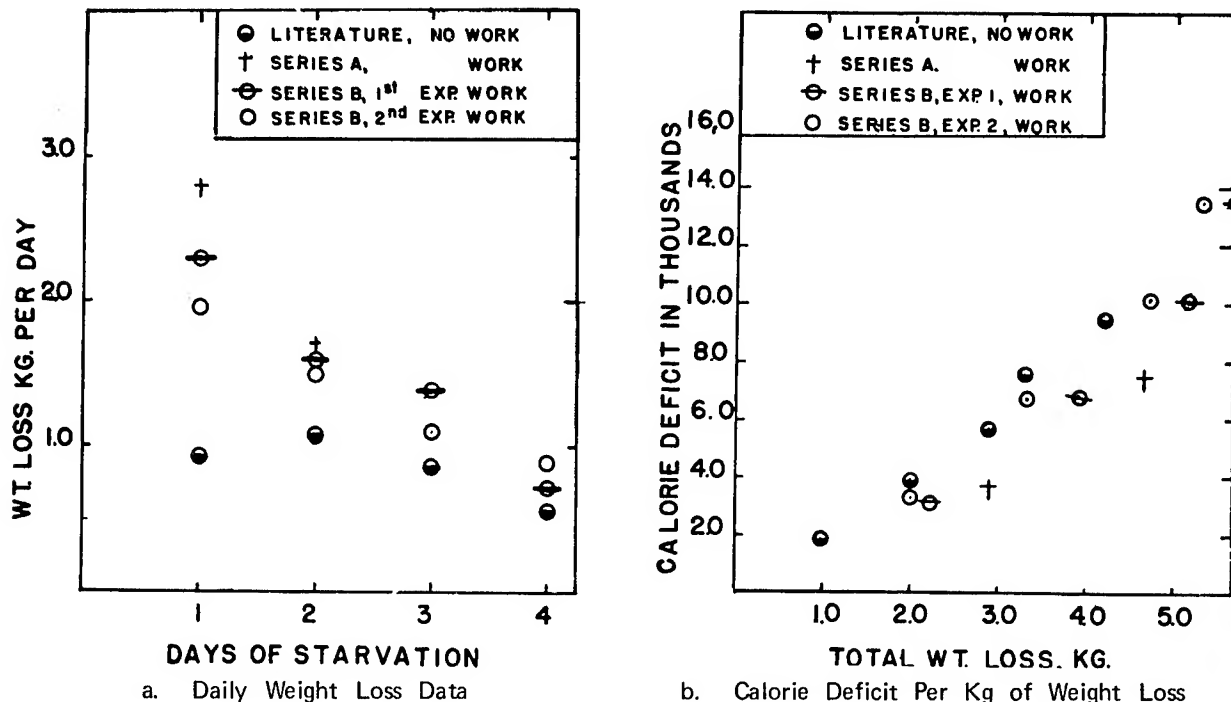
In the rare situation where lack of food and water and not lack of oxygen stores limit survival, the effect of starvation on performance must be considered. The lack of water has been covered in Water (No. 15).

It is clear that the decline in human performance during starvation is a critical factor in a survival situation. Both acute and chronic starvation affect the physical and mental ability of the subject to extricate himself from his environment and also affect his psychological set. Anxiety is a major factor to be considered. The design of optimum survival rations has already been mentioned above. The response of humans to starvation has also received much study (15, 17, 49, 54, 91, 97, 101). The effects of acute starvation accompanied by hard work on the well-being and performance of man are of special interest and importance in certain emergency situations.

The results of the two most extensive studies to date on acute starvation will be presented to define the problem (15, 17, 91). Because of the uniqueness and importance of these data in space emergencies, they will be covered in detail.

Figure 14-18

Comparison of Weight Losses and Calorie Deficit Per Day in Young Men
Who Were Starving With and Without Work
(After Taylor et al⁽⁹¹⁾)



The data on men starving without work were drawn from the literature (See original paper for literature sources and text for details.)

Weight losses and calorie deficits were calculated from the morning of the first day of fasting to the morning of the last day of fasting.

Five-Day Starvation with Exercise

Figure 14-18 presents the weight loss and caloric deficit of the men in the first study. The body weight losses of eight men who had merely starved for five days at rest in several different studies were compared with men who worked. Water was given ad libitum. Four men were subjects for a 2.5-day fast (Series A) and twelve men for a 5-day fast (Series B). The average total caloric deficit in Series A was estimated to be approximately 9,000 while in Series B it was approximately 16,000 Cal. The mean weight loss in the first series was 4.5 kg. (6.7 percent) and that in the second 5.5 kg. (7.8 percent). The men walked at 3.5 m. p. h. on a 10 percent grade (an average expenditure of 550 Cal. per hour) for 4 hours each day in Series A and for 3 hours daily in Series B. In addition, one maximal performance test (running at 7 m. p. h. on a grade for 3 to 5 minutes) was carried out each day.

The 2.5-day fast with hard work resulted in 6.8 percent body weight loss while the 4.5-day fast produced an 8 percent loss in body weight. The daily loss of weight in both conditions is seen in Figure 14-18. It will be noted that on the first day the men performing work lost 2 to 2.5 times as much weight as the men who were not performing special work tasks. But by the fourth day, this ratio had decreased to 1.2 to 1.4.

Aerobic work of this type was carried on with few signs of loss of fitness during the first day. On the morning of the second day, work pulse rates were increased by 10 to 15 beats per minute, work ventilation was increased, and the blood sugar during work decreased 25 mg. per 100 ml. Only a small increase in work pulse rate (5 beats per minute) was noted during the remainder of the fasting period. The men were able to complete their walking assignments in all cases except for one individual who was forced to stop walking on the fourth day because of nausea and gastric distress. All the men complained of fatigue, sore muscles, and weakness of increasing intensity as the experiment progressed. Nausea and occasional vomiting were common complaints, particularly after the bouts of anaerobic work. Pain in the side frequently accompanied exhausting work.

Mechanical efficiency of grade walking decreased from 19.0 to 17.8 percent. This decline was paralleled by a decrease in the nonprotein respiratory quotient and an increase in the relative amount of fat metabolized during work. The ability to perform exhausting "anaerobic" work was definitely impaired after the first day of starvation. On the second day of starvation the score of the Harvard Fitness Test was decreased to 70 percent of the control value and on the fourth day the score had dropped to 40 percent. It would appear that alteration of neither circulatory nor respiratory function was important in the decreased performance of the Harvard Fitness Test, but that decreased efficiency of muscular work and the development of pain and other distress were involved. The oxidative energy available during anaerobic work was well maintained as shown by the fact that there was no change in the maximal oxygen intake per kilogram of body weight during the fourth of the 5-day fast. The physiological response to a fixed anaerobic task showed no deterioration at the end of the first day as measured by the blood lactate concentration. However, there was a definite increase in blood lactate concentration and in the 10-minute oxygen debt on the fifth day of the fast.

Strength was not affected while measures of speed and coordination showed some decline during the starvation period. This loss of speed and coordination appeared to be dependent on the blood sugar concentration and could be reversed easily with the administration of 100 gm. of sugar (49). Deterioration in the psychomotor area followed the same general pattern of maintenance of good performance on the first day with definite deterioration on the morning of the second day. Table 14-21 (acute starvation) compares performance with that found in another semistarvation experiment. Recovery of performance was studied after 4 and after 5 days of refeeding. At this time the body weight had returned to the control (pre-fast) values. On the fourth day the ability to perform anaerobic work was found to be completely recovered. On the fifth day, the pulse rate during the walk was 4 beats less than that of the control period. The 10-minute oxygen debt and the blood lactate concentration 12 minutes after a fixed task of anaerobic work had returned to normal levels. The maximal oxygen intake was 2 percent less than the control value and there was a small amount of over-ventilation present during both work and recovery. It is concluded that the physical deterioration associated with the loss of 40 to 50 gm. of nitrogen under these conditions is repaired within 3 to 5 days of refeeding.

For twelve young men the 4.5-day fast with hard work resulted in an 18 percent decrease in plasma volume and an 8 percent loss in extracellular volume measured by the thiocyanate space. This loss of fluid accounted for 27 percent of the total body weight loss of 5.5 kg. During refeeding after the 4.5-day fast, the initial body weight was recovered in 3 to 5 days of refeeding. The plasma volume and thiocyanate space were 12 to 8 percent, respectively, above the control values. The increases in these spaces accounted for 30 percent of the weight gain during the first four days of recovery. Dysorthostasia may result from this factor.

At the end of 3.5 days of starvation with hard work, one man showed unequivocal jaundice, the liver function tests demonstrated definite malfunction of the liver. The mean 1-minute serum bilirubin of ten men increased from 0.11 mg. per 100 cc. before starvation to 1.27 mg. at the end, and the total bilirubin rose from 0.76 to 1.96 mg. per 100 cc. The 4-hour urobilinogen excretion increased from 1.13 to 2.96 mg. All liver function tests had returned to normal by the third day of recovery. Observations on four men who starved and worked for 2.5 days showed that: (a) nitrogen loss was not affected by the additional caloric expenditure required by the physical work; (b) acetone excretion in significant amounts began on the first day of starvation; (c) resting blood sugar fell 15 mg. per 100 cc. blood by the morning of the second day; and (d) the resting respiratory quotient was depressed to 0.71 on the morning of the second day. Although acetone excretion in significant quantities begins earlier in starvation with work, the quantities excreted per unit of calorie deficit were not different in the two conditions.

Ten Day Starvation

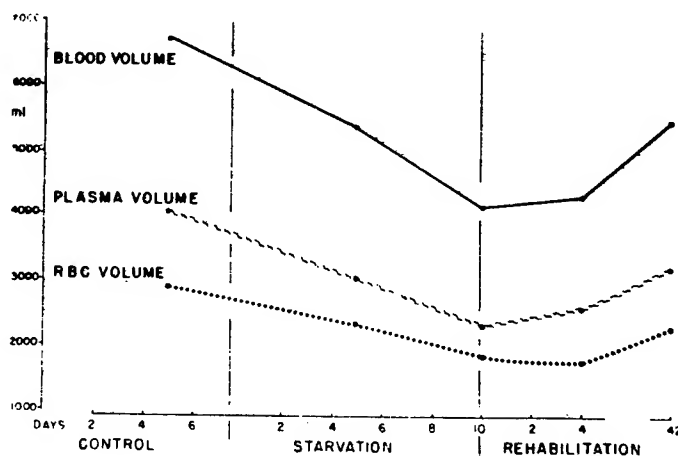
The second study extended starvation to ten days with fluid given ad libitum (15, 17). Body weight decreased progressively for the six male subjects averaging 1.44 kg on day one and 0.35 kg on day 10. Total weight loss averaged 7.27 kg or 9.5%. Fluid balance (sensible and insensible loss) averaged 1.2 kg/man on day 1 and 0.36 kg on day 10. Figure 14-19a represents the loss in blood plasma, and r.b.c. volume during starvation recovery. Figure 14-19b repre-

Figure 14-19

Blood and Metabolic Changes During 10 Days of Starvation
with Water Ad Libitum

(After Consolazio et al⁽¹⁵⁾)

a. Blood Plasma and Red Cell Volume



b. Daily Mineral Excretion in Urine,^a
Average/Man Per Day

Phase	Sodium, g	Potassium, g	Calcium, mg	Magnesium, mg	Chloride, mEq
Control	2.99	2.12	125	93.4	92.3
Starvation					
Day 1	2.32	2.10	104	69.9	84.8
2	1.84	1.54	141	111.6	38.2
3	1.77	1.58	107	170.0	12.1
4	1.98	1.77	156	150.5	11.8
5	1.95	1.50	166	94.2	9.0
6	1.98	1.59	157	114.4	12.1
7	1.87	1.56	151	75.2	10.0
8	1.78	1.30	126	68.9	9.4
9	1.67	1.21	104	67.0	7.5
10	1.56	1.12	67	37.6	6.8
Rehabilitation					
Day 1	2.00	1.44	117	45.4	23.6
2	3.33	2.06	175	40.9	72.5
3	4.12	2.31	193	37.7	97.2

^a Values are means of 6 men.

c. Blood Electrolyte Changes,^a mEq/liter

Phase	Calcium	Magnesium	Sodium	Potassium
Control	4.8 ± 0.3	1.63 ± 0.10	147.7 ± 3.4	5.6 ± 0.4
Starvation				
Day 1	4.7 ± 0.4	1.83 ^a ± 0.14	147.7 ± 5.7	6.1 ^a ± 0.2
5	4.5 ± 0.1	1.90 ± 0.36	142.4 ^a ± 3.9	4.6 ^a ± 0.5
10	4.5 ± 0.1	1.80 ^a ± 0.00	142.1 ^a ± 1.8	4.5 ^a ± 0.4
Rehabilitation				
Day 4	4.3 ^a ± 0.2	1.75 ^a ± 0.05	142.1 ^a ± 1.4	4.6 ^a ± 0.2
16	4.3 ^a ± 0.1	1.75 ^a ± 0.05	143.6 ± 3.3	4.3 ^a ± 0.5
24	4.9 ± 0.3	1.85 ^a ± 0.10	155.4 ± 8.0	5.3 ± 0.6
40	4.7 ± 0.3	1.70 ^a ± 0.06	147.0 ± 4.5	5.1 ^a ± 0.1

Values are means ± SD.

^a Significantly different from control values.

sents the mineral excretion and Figure 14-19c the changes in blood electrolyte. Large excretion of urinary nitrogen reflected protein catabolism. Other metabolic findings are detailed in References (15) and (17). Abnormal EKG's were noted in all subjects (17) and one subject had an abnormal EEG.

At the end of 10 days, the men were in poor condition mentally and physically with weakness and apathy noted. There was frequent lapse of memory, slowness in answering questions, and mental retardation. Muscle cramps were noted, probably due to intramuscular sodium deficiency (miner's cramps). Performance data are noted in Figure 14-20. The curves of Figure 14-20a show that oxygen uptakes and RQ are significantly altered during fasting. In Figure 14-20b submaximal treadmill work \dot{V}_E BTPS and \dot{V}_{O_2} weight are shown to be decreased during both starvation and rehabilitation, probably indicating a training effect. The decrease in maximum aerobic capacity in Figure 14-20c during fasting was not statistically significant. Other maximal work measurements such as \dot{V}_E BTPS pulse rates, and kg-meters of work per minute were altered in such a way during the rehabilitation period as well as during starvation as to indicate a training effect. Oxygen equivalents in liter of air ventilated per liter oxygen absorbed (STPD) decreased during starvation although the changes were not statistically significant. Oxygen pulses decreased slightly during fasting and oxygen debt after maximal performance decreased significantly from 5.3 to about 3 liters after 4 days of fasting and remained reduced during 4 days of rehabilitation. This suggests defective anaerobic metabolism. Other respiratory functions were not significantly changed.

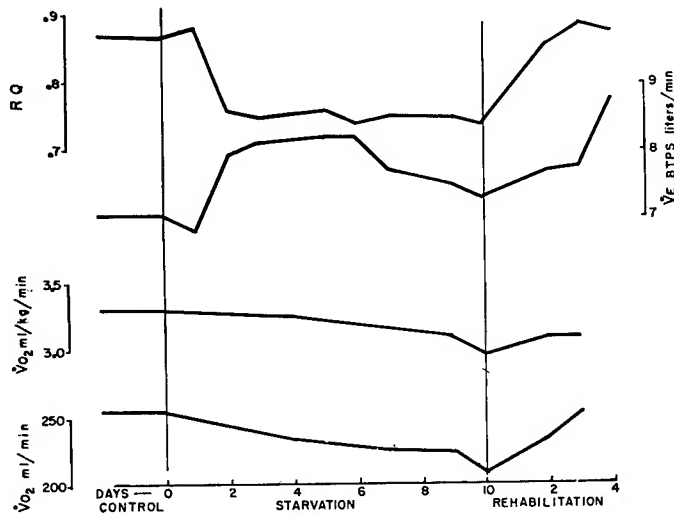
It should be noted that in one other 5-day acute starvation study, an average decrease of 31.6% in aerobic work capacity was reported (54). In the 4, 5, and 10-day studies reported above, there were no real differences in maximum aerobic capacity between control and fasting periods when the data were reported on a ml/min/kg basis. Anaerobic work was definitely impaired in both studies. The physiological basis for degradation of physical work performance during acute starvation is now under study (31, 60).

It appears that the rate of development and the degree of acidosis and dehydration attained are important contributing factors to the loss of fitness. This is especially important in arctic survival where the cold induces a diuresis and this, in turn, increases salt loss, dehydration and acidosis which reaches a peak at the end of three days (76). Orthostatic intolerance will probably increase with dehydration (see zero gravity environment, No. 7, page 7-116). It should be considered that the diuresis of early weightlessness may make an astronaut more sensitive to the dehydration and acidosis of starvation, especially if cold stress is present and vice versa. The additivity of these dehydrative stresses requires further study.

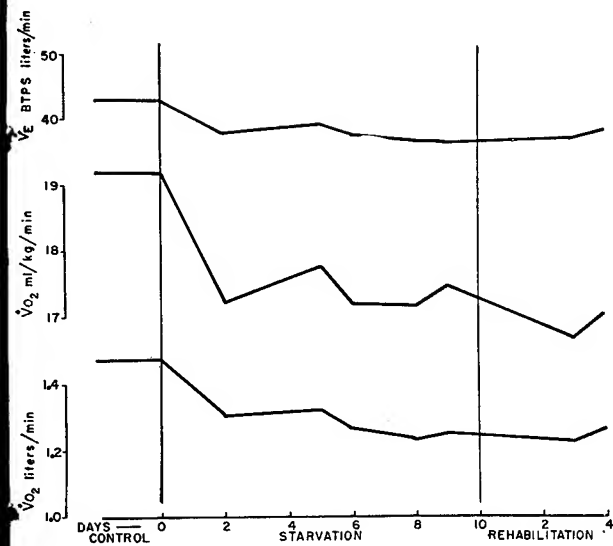
Current studies are focused on the relative effect of 400 Gm carbohydrate versus carbohydrate plus mineral supplement on the ketosis of acute starvation (52). Mineral supplementation with carbohydrate appears better since it reduces the great loss in body water and maintains a better mineral balance. Ketosis is ameliorated but negative nitrogen balance is only slightly improved, if at all. An optimum emergency ration of carbohydrate and minerals is needed for operations where acute starvation is a major hazard (45).

Figure 14-20

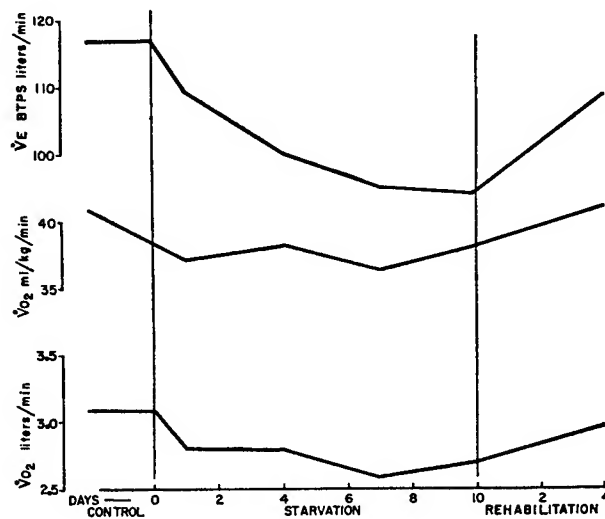
Exercise Performance During 10 Days of Starvation with Water Ad Libitum
(See text)
(After Consolazio et al⁽¹⁵⁾)



a. Basal Metabolic Rate Measurements



b. Submaximal Work Measurements
(Note training effect)



c. Maximal Work Measurements
(Differences not significant)

Semistarvation

Degradation of performance after acute total starvation must be contrasted with the effects of a loss of 24 percent of the body weight and 430 gm of nitrogen as a result of six months of semistarvation (Figure 14-21) (49). During semistarvation there was a 41% increase in plasma volume and a 43% increase in extracellular fluid volume. The semistarved individual performs grade walking with no increase in the work pulse rate but finds that sustained performance of this type is difficult because of muscular weakness. Measurements of static strength show a marked deterioration. The semistarved individual's capacity for anaerobic work is markedly reduced (70 percent as measured by Harvard Fitness Test). The maximal oxygen intake per kilogram of body weight falls 25 percent and the ability to produce lactic acid during anaerobic work was definitely deficient. This deterioration in performance produced by semistarvation was not easily reversed. It takes up to 20 weeks of intensive refeeding for measures of fitness such as the maximal oxygen intake and the Harvard Fitness Test to return to normal.

The sub-tables of Table 14-21 compare the degradation in psychomotor performance after several different stresses with that following acute, total- and chronic semistarvation. The experimental conditions can be summarized as follows:

1. Semistarvation. The food intake was decreased from 3,500 cal. per day to 1,570 cal. per day for a period of 24 weeks. The stress resulted in a decline of body weight from 69.4 kg. to 52.6 kg (49).
2. Acute starvation with hard work. The men ate no food (water ad libitum) and walked on the motor-driven treadmill for four hours daily with interposed rest periods. These conditions resulted in a caloric deficit of from 3,500 to 4,000 cal. a day. (See Figure 14-18).
3. Hard physical work. The experimental regimen involved an abrupt increase in the amount of aerobic work. This was accomplished by increasing the assigned treadmill work from one hour a day at 3.5 m. p. h. on a 10 percent grade to six hours a day for two days and four hours a day for the third day. One-half hour of rest was allowed between work periods. This increased the approximate daily energy expenditure from 3,500 to 5,800 cal.
4. Heat Stress. Unacclimatized subjects were placed in experimental rooms with temperatures maintained at 115° to 120° F during the day time and 90°F at night, with a low humidity (25 percent). Work consisting of seven 10-minute periods of walking on a motor-driven treadmill at 7.5 percent grade and 3.5 m. p. h. alternated with 10-minute rest periods, was carried out on each half day of the experiment. Water was allowed ad libitum.
5. Lack of sleep. The stress consisted of a sleep deprivation of 62 hours. The physical activity was kept at the accustomed moderate level.

Figure 14-21

Comparative Effects of Acute Starvation, Chronic Semistarvation,
and Several Other Stresses on Performance(After Brozek and Taylor⁽⁶⁾)

a. Handgrip Dynamometer, Kg

(S. D. = 8.3, based on N = 34.)

Stress	N	Mean change	F-test	D. R. †
Semistarvation	32	-16.4	214.95**	-1.98
Acute starvation	12	+ 0.5	0.26	+0.06
Hard work	10	- 2.8	36.00**	-0.34
Heat	12	- 2.7	18.53**	-0.33
Lack of sleep	12	+ 0.2	0.05	+0.02

b. Back-Pull Dynamometer, Kg

(S. D. = 27.8, based on N = 29.)

Stress	N	Mean change	F-test	D. R.
Semistarvation	29	-49.7	179.32**	-1.79
Acute starvation	12	- 7.2	3.97	-0.26
Hard work	9	-12.2	16.21**	-0.44
Heat	11	-15.3	12.69**	-0.55
Lack of sleep	10	- 7.1	7.68*	-0.26

c. Two-Plate Tapping, Number of Taps Per
10 Seconds

(S. D. = 5.4, based on N = 34.)

Stress	N	Mean change	F-test	D. R.
Semistarvation ξ	32	- 3.3	34.10**	-0.61
Acute starvation	12	-10.3	28.04**	-1.91
Hard work	10	- 1.7	5.41*	-0.31
Heat	11	- 1.7	1.61	-0.31
Lack of sleep	12	- 1.0	4.34	-0.19

d. Speed of Hand and Arm Movements, Number
of Times a Ball Is Passed Through a Vertical
Pipe in 1 Minute

(S. D. = 5.9, based on N = 34.)

Stress	N	Mean change	F-test	D. R.
Semistarvation ξ	32	- 3.9	31.49**	-0.66
Acute starvation	12	-11.0	16.78**	-1.86
Hard work	10	- 5.2	16.49**	-0.88
Heat	11	- 4.3	4.15	-0.73
Lack of sleep	12	- 3.5	7.19*	-0.59

 ξ Paper-and-Pencil version of the test ξ Performed standing, not on the treadmill

* Change significant at the 5 percent level.

** Change significant at the 1 percent level

$$\dagger \text{ Displacement Ratio (DR)} = \frac{M_C - M_E}{SD}$$

where M_C = control mean M_E = experimental meanSD = estimate of the standard deviation
of the control population

+ = "improvement", - = "deterioration"

Figure 14-21 (continued)

e. Complex Reaction Time, in 1/100 Second

(S. D. = 3.6, based on N = 34.)

Stress	N	Mean change	F-test	D. R.
Semistarvation	32	+ 3.2	26.59**	-0.92
Acute starvation	12	+ 9.0	19.80**	-2.50
Hard work	10	+ 2.1	11.37**	-0.58
Heat	11	+ 3.1	7.57*	-0.86
Lack of sleep	12	+ 1.4	5.65*	-0.39

f. Pattern Tracing, Number of Error Contacts

(S. D. = 13.3, based on N = 34.)

Stress	N	Mean change	F-test	D. R.
Semistarvation	32	+ 20.6	130.42**	-1.55
Acute starvation	12	+ 9.8	17.12**	-0.73
Hard work	10	+ 7.6	8.93*	-0.57
Heat	11	+ 6.4	3.76	-0.48
Lack of sleep	12	+ 0.1	0.00	0.00

g. Pattern Tracing, Length of Error Contacts in 1/4 Second

(S. D. = 7.5, based on N = 34.)

Stress	N	Mean change	F-test	D. R.
Semistarvation	32	+ 6.1	68.29**	-0.81
Acute starvation	12	+ 8.5	31.48**	-1.13
Hard work	10	+ 3.7	4.28	-0.49
Heat	11	+ 5.6	7.18*	-0.75
Lack of sleep	12	+ 4.0	9.69**	-0.53

The psychomotor tests were given daily in all the short-term stresses. For the present purposes only the maximal changes will be given. These changes represent the terminal period of the stress, the important exception being the heat stress in which the maximal changes occurred on the evening of the first day. In the semistarvation experiment the data were obtained in the last two weeks of the 24-week period of reduced food intake. The standard deviations SD and number of subjects in control N are recorded. Dynamometer grip studies in the 10-day starvation study noted above were significantly less than the control only on the 9th day of the study (54).

Following prolonged starvation, realimentation with high caloric diets constitutes a severe cardiovascular, gastrointestinal and general stress which can endanger life (39, 40, 76, 97, 101). This is most pronounced with diets of high carbohydrate. An increase in pulse rate and blood pressure is seen which may lead to heart failure. Realimentation must, therefore, be slow with broths of low carbohydrate content. This approach is recommended after retrieval of chronically starved crewmen in space operations.

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15. WATER

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The statement of water requirements for man in space operations must include an analysis of water balance in normal and emergency modes, as well as the purity standards for water.

Water Balance

In the adult man, water is approximately 60% of the body mass (73% of the lean body mass) and varies with age, fat content, and prior hydration. Body water is found in the cells of the body, around the cells, and in the blood vessels and lymphatic vessels. Each of these sites or compartments contains a given proportion of the total body water, with a division as follows: 2/3 of the total body water is in the cells (approximately 40% of lean body mass); 1/3 of the total body water is extracellular (approximately 20% of lean body mass), of which 1/4 is in the blood plasma and lymph (5% of lean body mass) and 3/4 in tissue fluid lying between the cells but outside of blood and lymphatic vessels (15% of lean body mass). The chemical anatomy of the several water compartments is known and is of great value in analyzing pathological states of hydration (24).

The internal water balance between the three body compartments is very much influenced by the continual and obligatory exchange of water between the man and his environment. There are continuous, obligatory losses of water from the body, that is, in the urine and feces and from the skin and respiratory tract. These losses are necessary for the purpose of carrying away waste products and also for temperature regulation; they must intermittently be made up by water taken in as liquid or as water in food or as the water produced chemically in the metabolism of food. Imbalance over a long enough period of time will produce dehydration or a water excess (overhydration) leading to edema (swelling), either of which has serious clinical consequences.

Water exchange in the intestinal tract is also sizable. In addition to the water ingested with food or taken in as liquid, a great deal of water is secreted along with digestive enzymes into the mouth, stomach, and intestines; water is re-absorbed later in the large intestine, with a small residue coming out in the feces.

A diagrammatic summary of the water exchanges between man and his environment is shown in Figure 15-1. Notice that the diagram shows the alimentary tract as being "outside" the body, and that large quantities of fluid move in and out of the alimentary tract during the course of a normal day. The diagram also makes it clear that vomiting or diarrhea would result in large losses of fluid as well as electrolytes. If either of these conditions persist, water balance is seriously upset.

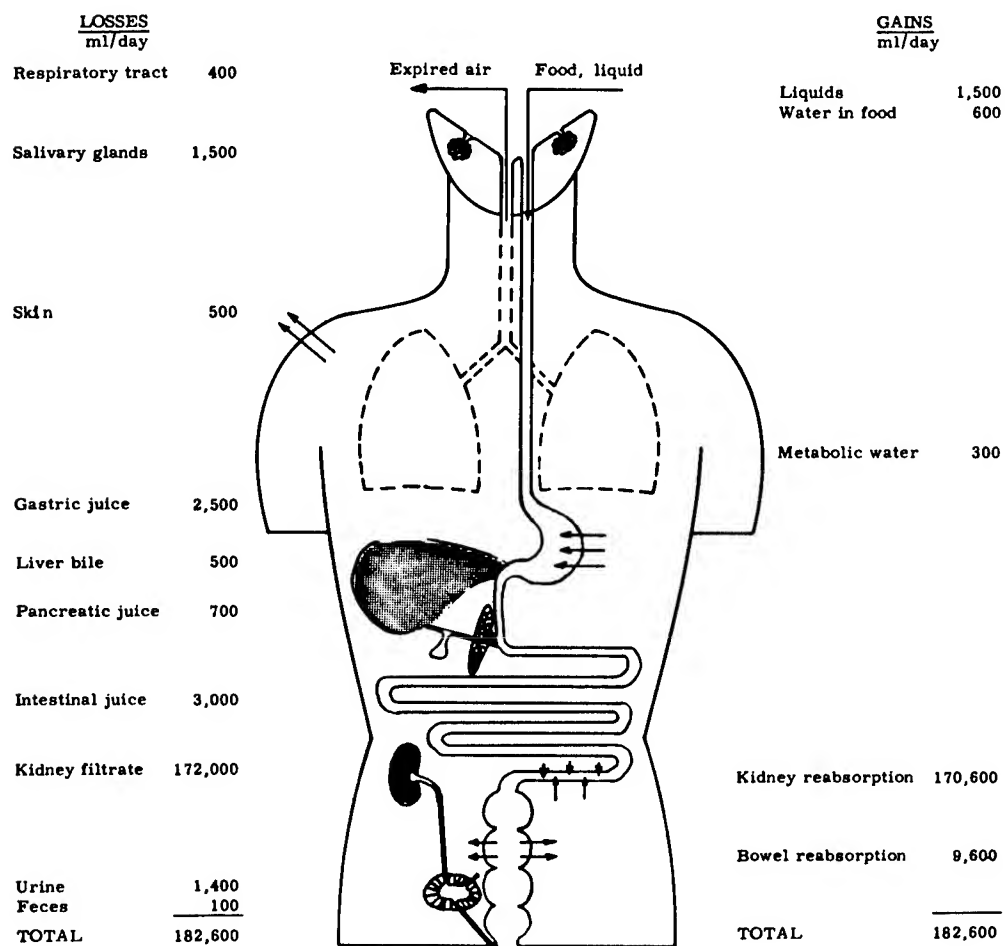


Figure 15-1

Diagram of Water Exchanges Between Man and Environments

(After Webb (108))

Water balance is defined as the difference between the input from all sources into the exchangeable water pool and the output from all sources as indicated in Table 15-2.

For primary factors in the calculation of water balance in logistic analysis it can be assumed that a male subject is at rest, quiet and comfortable and at a steady state so that such secondary factors in Table 15-2 as H_2O poly, H_2O nonexch, H_2O hydr, and H_2O assoc, H_2O milk or H_2O misc. may be eliminated and the following balance equation used:

$$H_2O_{\text{balance}} = (H_2O_{\text{fluid}} + H_2O_{\text{food}} + H_2O_{\text{ox}}) - (H_2O_{\text{fecal}} + H_2O_{\text{pulm}} + H_2O_{\text{derm}} + H_2O_{\text{urine}})$$

Details are available on the extension of such an equation relating water balance to manifestations of metabolic activity as changes in body weight ($W_2 - W_1$), solids ingested (Sol_{ing}), solids excreted (Sol_{fecal}) and (Sol_{urine}), urinary nitrogen excretion (N_u) and respiratory activity such as oxygen uptake ($O_{2 \text{ abs}}$) and CO_2 expired ($CO_{2 \text{ exp}}$). The modified Peters-Passmore equation is (17, 36,72):

Figure 15-2

Sources and Avenues of Input and Output for the Exchangeable Water Pool

(After Johnson (36))

Source or avenue	Input	Output
Gastrointestinal-----	Beverage (H_2O_{fluid})----- Moisture in food (H_2O_{food})-----	Feces (H_2O_{fecal}) Vomit or saliva
Pulmonary-----	Absorption of gaseous or fluid water (H_2O_{pulm})	Vaporization (H_2O_{pulm})
Dermal-----	Absorption of gaseous or fluid water (H_2O_{derm})	Transpiration (H_2O_{derm}) Sweat (H_2O_{sweat}) Milk (H_2O_{milk})
Renal-----	-----	Urine (H_2O_{urine})
Circulatory-----	Infusion or injection (H_2O_{misc})-----	Hemorrhage (H_2O_{blood}) Exudation or transudation (H_2O_{misc})
Metabolic (H_2O_{met})-----	Oxidation (H_2O_{ox})----- Condensation or polymerization (H_2O_{poly}) Release of nonexchangeable water of hydration (H_2O_{nonexch})	Hydrolytic reactions (H_2O_{hydr}) Water associated with protein, fat, or glycogen (H_2O_{assoc})

$$\begin{aligned}
 H_2O_{\text{balance}} = & (W_2 - W_1) + (1.3349 \text{ CO}_{2, \text{exp}} \\
 & - 0.9566 \text{ O}_{2, \text{abs}} - 1.04 \text{ N}_u) \\
 & + (\text{Sol}_{\text{urine}} + \text{Sol}_{\text{fecal}} - \text{Sol}_{\text{ing}})
 \end{aligned}
 \quad (2)$$

In this equation, all values are given in grams. Examples of its use and limitations are available (36).

The exchange of water with the environment under basal conditions can be depicted as a balance diagrammatically as shown in Figure 15-3. In this diagram a normal or standard value for water intake and water output is shown in large letters and beside each value is shown a range of high and low values which may occur under certain conditions. As the diagram suggests, if intake exceeds output, there may be an accumulation of excess water in the tissue spaces, which is edema. Conversely, if water loss exceeds water intake, a deficit is initiated and as it accumulates, progressively severe symptoms from dehydration appear and lead ultimately to death. The pointer scale on the diagram is marked in terms of percent of body weight either gained or lost.

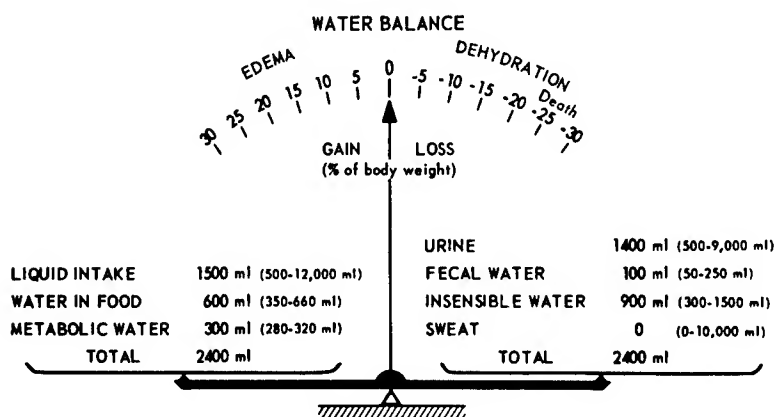


Figure 15-3

Diagram of Normal Water Balance

(After Kanter and Webb (38))

Water Requirements

The practical water requirements in space operations have been analyzed: (7, 38, 59, 62, 63, 108, 111, 112). The amount of water required is a complex function of activity, local temperature, humidity, windspeed, ambient atmospheric pressure and composition as well as adequacy of the cooling system in the space cabin suit environment (76, 108). In extravehicular operations the ambient thermal conditions and adequacy of the thermal control system of the suit are key factors. The general relationship between ambient temperature and fluid intake on Earth is seen in Figure 15-4.

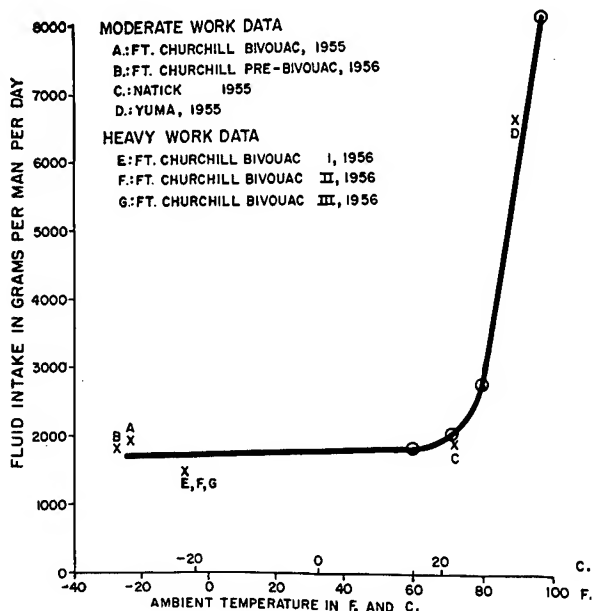


Figure 15-4

The Relation of Fluid Intake and Mean Ambient Temperature for Military Personnel

(After Welch et al (110))

Water Requirements in Normal Operating Modes

Review of the actual fluid requirements in space flight has prompted the Space Medicine Advisory Group to recommend that the amount of ingestible water per man should be 2.5 liters per day (1 cc per calorie of food) (104). This value may be high for a sedentary astronaut in a comfortable thermal environment (58). Water intake should be sufficient to maintain the urine at a specific gravity of 1.015 or less at a volume of at least 1 to 1 1/2 liters per day to avoid the development of urinary gravel and should be consumed in definite quantities on a programmed schedule (12, 30). This recommendation is for sedentary astronauts inside an orbiting vehicle within a cabin functioning at a normal comfortable mode.

In the more variable environment of the Apollo mission the general water requirements have been geared to the metabolic and space suit parameters as shown in Figure 15-5. (7). The estimates have been made for men of 2.0m² surface area with no arbitrary safety factors added. The Earth reentry phase is not considered as a special case. The routine operation of the LEM is inside pressure suits and on duty all of the time. Emergency decompression of the command module assumes pressurized suits and activity at 150% greater than normal on-duty load. It is also assumed that there is no convective or radiative loss to the cabin. In the LEM emergency decompression, the same elevation of work output is assumed as in the command module in emergency mode. On the lunar surface, the maximum continuous metabolic rate is 1600 BTU/hr with peak loads of 2000 BTU/hr. The lunar suit will be capable of limiting sweat loss to 100 gm/hr (.22 lb/hr) by providing a heat loss of about 2000 BTU/hr. (117). (See Figure 6-52a). Emergencies such as failure of cabin ventilation or suit cooling may superimpose higher thermal loads and water losses.

Studies of water requirements in space cabin simulators have elucidated the interaction between dietary, thermal, and atmospheric variables in determining water consumption (58, 88). In a series of 11 experiments

Table 15-5

Estimates of Metabolic Rate, Thermal Balance, and Water Requirements for Apollo Crew Members
(See text)
(After Billingham (7))

			COMMAND MODULE ROUTINE FLIGHT	COMMAND MODULE EMERGENCY DECOMPRESSION	LEM ** ROUTINE FLIGHT		LEM *** EMERGENCY DECOMPRESSION	LUNAR SURFACE EXTRAVEHICULAR (LCG OPERATION)*
Metabolic Rate Data	PER MAN		PER DAY	PER DAY	PER HOUR	PER DAY	PER HOUR	PER HOUR
	Heat Output	BTU	11,200	12,000	520	12,400	800	1,600
	Oxygen	lb	1.84	1.97	.085	2.04	.13	0.26
	Carbon Dioxide	lb	2.12	2.27	.098	2.40	.15	0.13
Thermal Data	Heat due to insensible water loss (Lungs, Skin)	BTU	2,600	2,700	115	2,750	150	250
	Latent Heat (Sweat)	BTU	1,370	7,430	170	3,990	572	230
	Sensible Heat to gas steam	BTU	7,230	1,870	235	5,660	78	0
	Sensible Heat to water	BTU	- - - -	- - - -	- -	- - - -	- -	1,120
Water Requirements Data	Urinary Loss	g	1,200	1,200	50	1,200	50	50
	Sweat Loss	g	597	3,240	74	1,740	250	100 max.
	Lung Loss	g	1,130	1,180	50	1,200	65	109
	Total Water Requirement	g	2,930	5,620	174	4,140	365	259
	Total Water Requirement	lb	6.5	12.4	.38	9.1	.80	.57

* LCG = Liquid Cooled Garment

** Both men are likely to be on duty most of the time

*** Work output per man will be higher than Command Module Emergency Decompression Phase

with 40 subjects, ad lib and total water intake were not altered by either dehydrated food, liquid food, continuously wearing pressure suits, or confinement in the AMRL Evaluator. However, an increase of 9°C in environmental temperature caused a three-fold increase in both ad lib water intake and insensible water loss and nearly doubled the total water intake. In four of eight ambient environment experiments, the mean ad lib water intake was less than one liter in two experiments, the mean total water intake was in the 1.5 to 1.8 liter range. In the last experiments of the series, pressurization in a full pressure suit with a pressure differential of 3.7 psi for four to five days caused a decrease in insensible water loss. The subjects subsisted on a 900 calorie Apollo contingency or emergency (39) diet containing less than 50 ml of water and had a total water intake ranging from 0.68 to 1.30 liters per day. (See Table 14-13) Insensible water loss (IW) and urine/total water (U/TW) index data were computed for all experiments. These data provide a means for assessing water balance under simulated space conditions.

For estimating the evaporative losses expected in unusual work, space suit or survival situations, Thermal Environment, (No. 6) should be consulted. Water requirements for sanitation purposes are covered below.

Minimum Water Requirements for Emergency Modes

Under emergency conditions of water limitation the minimal basal requirement for water becomes significant and may be the controlling factor limiting life. The absolute minimum obligatory output has been found to be 280-300 ml/day (24, 82). Assuming a minimal insensible H₂O loss of 500 ml/day and zero fecal loss, the total water input must equal 800 ml which is in close agreement with empirically derived value of 1 liter/day (82). This figure is the absolute minimum and is still hazardous in that it assumed that the environment is so controlled and stress-free that insensible loss is kept to its lowest level

and there are no excessive losses through excess activity, sweating, obligatory diuresis, and other pathways.

The water requirements above basal for increments in activity, osmotic load to the kidney and hyperventilation due to activity have been discussed in detail and are summarized in Table 15-6. (36, 108).

Table 15-6

Basal Minimum Water Requirement and Increments for Osmotic Balance,
Activity, and Thermal Environment of a 70 Kg Man

	(After Johnson (36))	References
Basal minimum	= Renal + Dermal + Pulmonary = 800 ml	(1, 6)
Renal increment for osmotic adjustment	= $\pm(\text{Predicted excretion, mOsm/}$ $\text{day}-400) \times 2$	(80)
Insensible water increment for caloric output	= $\frac{(\text{Estimated kcal above basal})}{0.58 \times 4}$	(6, 68)
Sweat increment for temperature, humidity, air motion, work, and clothing	= $6 \times (\text{predicted 4-hr sweat rate})$	(49, 52)
Pulmonary increment for hyperventilation	= $(\text{Estimated pulmonary minute}$ $\text{volume} - 10) \times (\text{Absolute}$ $\text{humidity of expired air} -$ $\text{Absolute humidity of inspired}$ $\text{air})$	(111)

Osmotic Increment. The obligatory water requirement for excreting the osmotic load brought to the kidney is about 200 ml per day for each increment of 100 milliosmols per day. There is an optimum; for intakes below about 700 milliosmols per day, there is a loss of body water attributable to hyposmotemia. For such a situation, increasing the water intake does no good; there is a loss of water by way of the kidney, which must have a normal osmotic load from which to elaborate urine.

Activity Increment. Under moderate conditions about 25 percent of the heat load is dissipated by the insensible water loss. Sweat has virtually the same heat of evaporation as water, 0.58 kcal per gram. A daily increase from resting at 2000 kcal to moderate activity at 3000 kcal will require an increment of about 400 ml of water (i.e., $1000 \times 1/4 \times 1/0.58$) for heat dissipation.

Thermal Environment. Although in formal algebraic respects the thermal heat load of the environment is equivalent to the caloric effect of activity, yet there is a physiological difference, and the combined impact of temperature and humidity and other factors must be accounted for (See Figure 15-5, Ref. 1, and sections on evaporative heat loss in Thermal, (No.6) (8, 108). The internal production of heat, especially in work, is mainly a mathematical function of body mass and external work rate. The dissipation of heat from the body and the effects of heat and humidity are mainly a function of the body's surface area. In Table 15-6, the formulation of the water requirement as related to the thermal environment is the predicted 4-hour sweat rate index of McArdle et al (49). This calculated sweat output, however, is for rather restricted conditions and is not valid where strenuous exercise is involved (8). For operations requiring space suit activity, other estimations must be made of evaporative water loss (108). This is especially true in liquid-cooled space suits where

uneven heating and cooling of the skin may alter the expected sweat response (13, 41). (See Figures 6-51 to 6-53.)

Figure 15-6 indicates that in contrast to the small savings in the water economy that can be made by juggling the osmotic balance and the aqueous vapor pressure of the ambient air, the losses that may be produced by changing the rate of dermal loss, pulmonary loss, and renal loss are large. Sweating may go on at the rate of a liter an hour all day long (20). Increasing the pulmonary ventilation from resting at about 10 liters per minute to moderate work at 30 liters per minute can increase the pulmonary loss by a factor of 3. On the other hand, an extra osmotic load equivalent to 10 g NaCl per day can increase the urinary water loss by only 300 ml per day. The turnover of total body water may range from 2 percent per day to more than 20 percent per day. Renal loss can, possibly, be safely reduced to 500 ml per day. Losses through the lung and skin may be minimized by reducing physical work, maintaining a cool environment with the highest practical humidity, and keeping sweating low by using other modes of heat loss such as conduction.

In calculating water requirements, the metabolic water available from food will play a role. Table 15-7 represents these relationships.

Table 15-7
Products of Oxidation of 1 Gram of Foodstuff in the Body
(After Peters (72))

Substance	O ₂ consumed, g	CO ₂ produced, g	H ₂ O produced, g	Heat produced, kcal
Monosaccharides, e.g., glucose.....	1.067	1.467	0.600	3.8
Disaccharides, e.g., sucrose.....	1.122	1.543	.579	4.1
Starch.....	1.185	1.629	.556	4.3
Fat (lard).....	2.876	2.805	1.071	9.3
Protein.....	1.382	1.522	.396	4.1
Urinary N ^a	8.638	9.513	2.475	25.6

^a The factor 6.25 is assumed to correct urinary N to protein catabolized.

By multiplying the total weight of each dietary component in grams times the grams of water per gram of foodstuff of Table 15-7 and summing the values, the total metabolic water is obtained. For the most diverse diets of 3000 kcal/day, a range of 300 to 400 gms/day of water can be expected. Thus, the nature of the diet offers little variation in metabolic water. Nomogram 14-6f of Nutrition, (No. 14) can be used for rapid estimation of metabolic water.

The osmotic increment over basal requirements for water may be critical in emergency conditions. There is an irreducible level of urine production related to the amount of electrolytes which must be excreted each day to maintain osmotic balance in the body. The kidney responds to a water deficit situation by excreting increasingly concentrated urine. The maximum osmotic level, or urine concentration which it can normally produce is about 1.4 osmoles/liter (24). The quantity of osmotically active material which must be

excreted each day is a function of the dietary composition. (See Table 15-8). On a pure carbohydrate diet, or a diet consisting of only fat and carbohydrate, the osmotic load is minimal. That is, the end products of metabolism of fat and carbohydrate do not produce electrolytes to be secreted in the urine, only water and CO₂. The metabolism of protein, however, does produce osmotically active material, principally urea. The minimum urine flow on a pure carbohydrate diet in the face of water deficit is 4 to 5 ml per hour (96 to 120 ml per day) whereas with a high protein diet, the minimum urine flow is 20 to 25 ml per hour (480 to 600 ml per day) (43).

In the face of an emergency demand for minimal urine flow to conserve water, the effect of the protein content of a 3000 kcal/day diet on minimum urine volume for the day would be as shown in Table 15-8.

Table 15-8
Dietary Control of Minimal Urine Volumes

	(After Webb (108))	
	<u>Total Solutes*</u>	<u>Minimal Urine Volume**</u>
Diet 1 (50% Protein)	1892 milliosmols	1400 ml/day
Diet 2 (30% Protein)	1212 milliosmols	880 ml/day
Diet 3 (10% Protein)	523 milliosmols	310 ml/day
Diet 4 (0% Protein)	180 milliosmols	100 ml/day

*Assuming constant low values for sodium 40 meq/day, chloride 65 meq/day, and potassium 70 meq/day, and computing urea from the quantity of nitrogen available in the protein of the diet.

**Using the average maximal concentrating ability of the kidney at 1.4 osM/liter.

Dehydration and Overhydration Syndromes

Dehydration means the failure of replacement of water and electrolytes through inability to find or take fluids and salts to make up for output. The spectrum of dehydration as a function of weight loss has been summarized in chart form as shown in Figure 15-9. The terminal sequence in fatal dehydration involves decreasing volume of extracellular fluid, near-complete retention of sodium salts through the action of the adrenal hormone, aldosterone, and a rising concentration of electrolytes all over the body (43, 50).

Of more immediate concern are the milder stages of water loss which might be expected to occur in space flight, and the effect of this minimal "dehydration" on performance and tolerance to stress. Small amounts of water loss can easily become cumulative if continued day after day, as experience with troops in hot climates has shown (2). In manned space flight, as experienced by both the USSR and the USA, a consistent weight loss of approximately 2-5% of body weight has occurred in every astronaut or cosmonaut (108,109). This consistent observation is apparently independent of the duration of flight, weight losses in this range having been recorded in flights of three orbits (4 1/2 hours) up to missions lasting 4, 8, and 14 days. Similar weight losses have been reported from some of the space cabin simulation work done at the USAF School of Aviation Medicine. Since water was freely

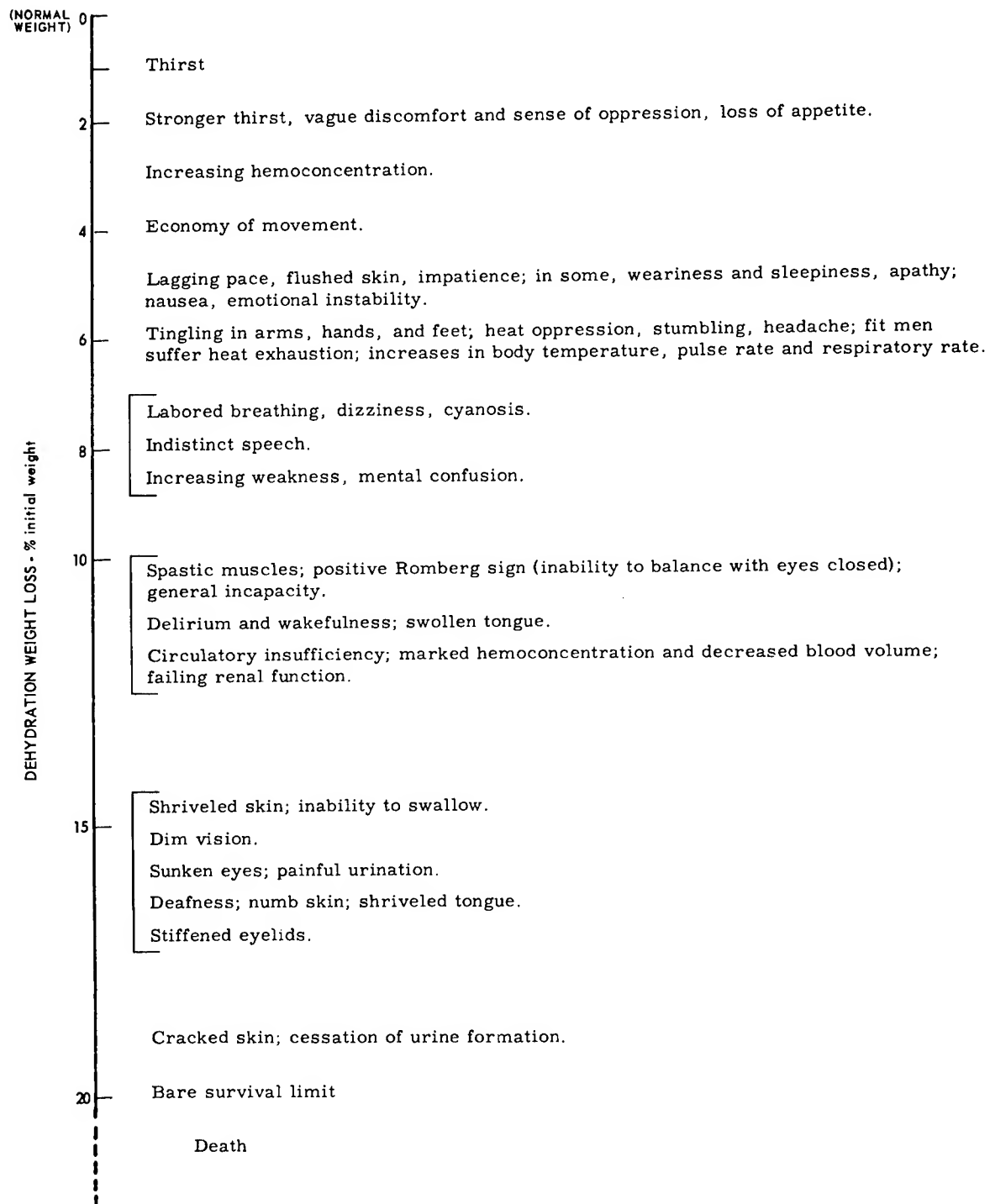


Figure 15-9

Spectrum of Dehydration

(After Kanter and Webb⁽³⁸⁾ from the data of Adolph⁽²⁾,
Beeson and McDermott⁽⁴⁾ and Goldberger⁽²⁵⁾)

available to these men, there remains a question of why they did not respond to the weight loss (water loss) by drinking.

The normal water replacement is triggered by thirst. The basic mechanism of thirst and its alteration by different conditions has received much study (31, 92, 96, 97, 107, 113, 114). Failure of water replacement in space flight has been analyzed as a manifestation of the "voluntary dehydration" of Adolph and Laddell (2, 76) and the "involuntary hypohydration" of Greenleaf (30). The process referred to is that seen in men who are working in heat or otherwise losing water at a high rate (8). These men seldom replace water as rapidly as it is lost, and during the period when body weight is reduced there is a water depletion which may amount to 1-2% of body weight. Many people in hot industrial situations and people who live in hot climates carry such a weight deficit through the day and make it up in the evening. Complete rehydration does not occur during the day because the men do not voluntarily increase their water intake sufficiently. Apparently neither water loss alone nor water and salt lost together produce thirst corresponding to a depletion of body water of 2-3% of body weight (30). It is thought that there are 2 liters of "free circulating water" which are expendable without gross physiological disturbance. In men who are habitually overhydrated, "voluntary dehydration" may possibly be a loss of this free circulating water. The effect of zero gravity on this response is not clear (108). In appropriate thirst responses or individual idiosyncrasy may precipitate a water deficit and must be guarded against by scheduled drinking (12, 52). Ideally, the rehydration should occur by taking small amounts of water frequently during the time the water loss is high. Drinking large amounts of water may produce diuresis, with a net loss of body water. Also drinking large amounts of water may provoke gastric distress and vomiting. It is better to make up water loss as it is occurring by continually drinking small amounts of water. By this method the body weight can be maintained unchanged in the face of sweat rates as high as 950 gm/hr (8).

The alteration of the physical and chemical properties of sweat and factors affecting the water balance in confined spaces is now under study (37).

The data of Figure 15-9 indicate the deficit in function which may be expected in more severe forms of dehydration. Dehydration in the range of only 1-3% of body weight causes a higher heart rate in submaximal work and a significantly decreased time to exhaustion to maximal work (10, 15, 42, 79). Walking time, especially in hot environments, can be reduced up to about 50% by dehydration of up to 4% (18). Isometric muscle strength begins to deteriorate at 4.0% weight loss; deterioration appears in a modified Harvard step test at 4-4 1/2%; submaximal oxygen intake for a given exercise deteriorates at greater than 4%(30). It has been shown that physiological strain can be reduced when men were required to work in hot, humid climates if before working they overhydrate by drinking two liters of water. This improvement was shown by a lesser strain in the overhydrated man than in men who replaced water only as it was lost (60).

Of special interest to lunar operations is the progressive decrease in orthostatic tolerance as water deficits of 1 to 5% are imposed (2, 5). Dehydration can synergize with heat and prior deconditioning by bed rest to exaggerate

orthostatic intolerance (19). Decrease in body weight of only 1-3% can decrease tolerance to positive (+G_z) acceleration (28, 29, 30, 99) (See also zero gravity in Acceleration #7).

The effect of varying degrees of dehydration on thermal sweat output is still open to question (15, 27, 71, 75, 81). The rate of dehydration, its chronicity, and simultaneous salt or food deprivation appear to be key factors in determining the response of thermal sweat rate to dehydration. Not clear is the extent to which the 2-3% dehydration in weightlessness will alter subsequent sweating responses during extravehicular operations.

Heat training leading to acclimatization for particular heat conditions of extravehicular, orbital, and lunar operations would be helpful in several ways (108). The sweating and cardiovascular response to heat stress would be more appropriate; the training would teach the subject when and how to drink to avoid dehydration; and he would be less likely to succumb to heat prostration during mild stress.

Survival time after water deprivation in space operations will be a complex function of many simultaneous thermodynamic variables (See Thermal (No.6). The data for survival time under different ambient conditions on Earth are given in Figure 15-10. These can be used for post-landing emergencies. For emergency situations, alleviating thirst by carbohydrate mouth coolants is under study (94). This may prolong the functional capacity in absence of water sources.

Advanced humidity control systems are now under study (73, 70). Failure of humidity control in suits and cabins may lead to annoying if not serious maceration and infection of the skin with secondary effects on human performance (14, 44, 46, 85, 98, 100, 108). The skin disorders that can arise from heat and excess humidity are: (98)

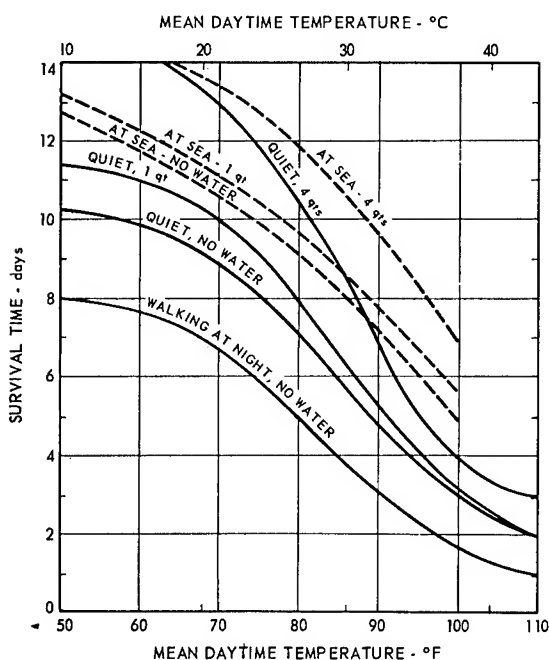


Figure 15-10

Effects of Water Deprivation on the Survival Time in Different Thermal Environments on Earth

Predicted survival times on land and sea are shown when men have no water, or 1 quart per man, or 4 quarts per man, total supply. The man on land is expected to rest, and not to try to walk out of the situation, but to stay in whatever shade he can muster. The effect of walking only at night is shown in the lowest curve. The survival time is set by dehydration.

(Adapted by Kanter and Webb⁽³⁸⁾ from data of Adolph⁽²⁾, Nutall⁽⁶⁸⁾ and U.S. Air Force⁽¹⁰²⁾)

Intertrigos--in the groin, axilla, and external otitis.

Superficial fungus infections--dermatophytosis, candidiasis.

Superficial pyodermas and cellulitis--folliculitis, furunculosis, tropical impetigo, etc.

Occlusion of pores and follicles--prickly heat (miliaria), tropical acne, and anhidrotic heat exhaustion.

A hydrated stratum corneum (the superficial layers of the epidermis) invites invasion and growth of bacteria and fungi. This hydration occurs particularly if sweat cannot evaporate, as would be true with the wearing of impermeable clothing (100).

The condition of prickly heat, or miliaria, is common in people in hot climates and particularly hot, humid climates. (44, 46). The condition can be annoying, or become more and more severe until the patient is disabled. The condition results from a plugging of the sweat-gland duct either superficially or deep. Miliaria and other anhydrotic disorders of the skin arising from poor moisture dissipation are currently under study (26).

Treatment of the various dehydration and overhydration syndromes in space operations has received recent consideration (14). It is hard to separate the thermal from the dehydrative aspects of the problem.

Wash and Waste Water Requirements

Past estimates for the minimum "wash" or sanitation water requirements have been from 500 to 1800 ml/man day depending on duration and type of mission (54, 101). Subjects have spent periods of 6 weeks in space cabin simulators without washing (85). There was severe body odor but no major problems. Lack of tooth brush water resulted in gingivitis. Estimates for missions of two or more months duration with moderate water restriction have run from 1 to 6 gallons/day (9, 16, 34, 64). In more advanced missions where less restrictive weight limitations may be in force, the water requirements may be expanded to encompass the more typical military and exploratory usage indicated in Table 15-11. The hygienic aspects of wash water requirements have been covered in a recent review (23). It is felt that normal earthly hygienic conditions including washing of clothes can be easily attained with 6-12 gallons/day, but that less than 6 gallons could easily be tolerated without too much inconvenience.

Table 15-12 covers the breakdown of "wash" water use projected for future space missions giving projected maximum and minimum for each category.

The handling of waste water is also a problem (33, 74, 93). Table 15-13 can be used as a rough estimate for inputs into waste storage or recycling systems. Simple arithmetic shows the impossibility of storing sufficient water for missions of about 1000 days. With a 10-man crew, each needing about 10 lbs. of water per day for all purposes, the total water requirement would be 50 tons, occupying almost 1700 cubic feet of space. Since present, or even foreseeable, booster capacity cannot accept such a penalty in weight or

Table 15-11

Comparison of Total Water Requirements

(After Celentano and Amorelli et al⁽¹⁶⁾)

a) Water Requirement in Military & Exploratory Situations.

Organization	Gallons Per Man-Day
IGY polar expedition	11
Military advanced bases (World War II)	
Allied	10
United States	25
U. S. Air Force	
Permanent bases	150
Advanced bases	75
U. S. Navy	
Permanent bases	100
Advanced bases	25 to 50
Surface vessels	25
Submarines	20
Space System	6
(Recommendation for Hygiene equivalent to that on Earth)	

b) Consumption of Fresh Water Aboard Ship.

Use	Gallons Per Man-Day
Drinking	0.5 to 1.0
Kitchen	1.5 to 4.0
Washing	5.0 to 20.0
Laundry	5.0 to 10.0

Table 15-12

Conservative Estimates of Daily Water Requirement for Sanitation Purposes
to Attain Hygiene and Comfort Equivalent to Earth Conditions

(After Roth⁽⁷⁷⁾ from data of Ingram et al⁽³⁴⁾)

	Liquid wastes, kg/man-day		Solid wastes, kg/man-day	
	Minimum	Maximum	Minimum	Maximum
Food preparation	1.0	4.0	0.010	0.040
Personal hygiene	1.5	4.5	.015	.045
Clothes washing	3.0	4.0	.030	.040
Cabin cleansing	1.0	5.0	.010	.050
Subtotal	6.5	17.5	.065	.175
Total	6.565 to 17.675			

Table 15-13

Daily Human Metabolic Waste Production

(After Roth⁽⁷⁷⁾)

	Reference					
	Liquid wastes, kg/man-day		Solid wastes, kg/man-day		Average metabolic wastes, kg/man-day	
	Minimum	Maximum	Minimum	Maximum		
CO ₂	1.0	1.0	-----	-----	1.03	1.03
Perspiration and respiration	.80	3.48	-----	-----	1.0 to 3.5	1.00
Urine	1.2	1.5	0.060	0.075	1.52	1.39
Feces	.053	.08	.017	.020	.182	.114
Total	3.13 to 6.155				3.732 to 6.232	3.534

volume, reclamation of water must be performed on lengthy, manned mission in space.

Advanced humidity control (70) and water recovery systems using isotop heating (22, 57) and vacuum distillation with vapor compression recovery of latent heat (67) are currently under study.

Water Purity

The standards for both "wash" water and drinking water must be considered. Potability standards for drinking water are being developed which will modify existing U.S. Public Health Service and World Health Organization Drinking Water Standards (103, 115). These are shown in Figure 15-14. In some areas these are overly stringent because of their applicability to the entire range of population through their whole lifetime including infants and the infirm (89, 91, 101, 103, 105). They protect aquatic life from chromates and copper and meet threshold limits of taste in the case of copper, iron, zinc, and manganese. They are standards of excellence but are probably far too severe as criteria for the maintenance of health and well-being for space crews. However, it also seems reasonable to require more stringent bacterial standards to cover long periods of storage after passage through water reclamation and recycling devices (48, 87, 89, 91). Summaries of the physiological effects of individual contaminants are available (89). Data are also available on the water-soluble atmospheric contaminants which may enter water supplies (90). (See Contaminants No. 13).

The following analysis is taken directly from a recent NAS-NRC review of water quality standards for long-duration manned space missions (61). In distribution of water to municipalities, it is possible to allow occasional failure to meet requirements fully, provided the failure is not great or prolonged and provided corrective measures are instituted promptly. In contrast, the standard recommended for water quality in space flight must be regarded for the most part pragmatically as performance standards to be met or exceeded by recovery systems during testing periods. Ability to test water for conformity with standards during actual flight will be minimal, except for sensory evaluation; and ability to take corrective measures, except for certain standardized procedures, will also be minimal. Because complete monitoring is not feasible, possible adjustments are limited, and the same source of water must be used whether it meets standards or not, it is intended that the recommended standards be met under all conditions of performance testing and on an individual basis, not simply on an average basis. It was recommended that performance testing be of sufficient duration to evaluate the quality of water produced by recovery systems not only when new and in prime condition, but also following some of the anticipated replacements and repairs to be done by crews during space flights. Trends in parameters of water quality should be given weight, as well as minimal attainment of numerical requirements. If deterioration in quality as measured by any parameter, occurs during the testing period, even though limits are not exceeded at any time, the testing should be prolonged until it is shown that requirements are still satisfied when steady-state operation has been achieved.

Determination	USPHS	WHO
Bacterial:		
Coliform bacteria, per 100 ml.-----	1.0	• 0.05 • 1.0
Physical:		
Turbidity, silica scale units.-----	5	-----
Color, cobalt scale units.-----	15	-----
Odor, maximum threshold num- ber.-----	3	-----
Chemical, mg/liter:		
Alkyl benzene sulfonate.-----	0.5	-----
Ammonia.-----	-----	• 0.5
Arsenic.-----	• 0.05	• • 0.2
Barium.-----	• 1.0	-----
Cadmium.-----	• 0.01	• 0.05
Calcium.-----	-----	• 200
Carbon chloro- form extract.-----	0.2	-----
Chloride.-----	250	• 350
Chromium (hexavalent).-----	• 0.05	• • 0.05
Copper.-----	1.0	• 3.0
Cyanide.-----	0.2	• • 0.01
Fluoride.-----	• 1.6-3.4	• 1.5
Iron.-----	0.3	• 1.0
Lead.-----	• 0.05	• • 0.1
Magnesium.-----	-----	• 125
Magnesium + sodium sulfate.-----	-----	• 1000
Manganese.-----	0.05	• 0.1
Nitrate, as NO ₃ .-----	45	• 50
Phenolic com- pounds.-----	0.001	• 0.001
Selenium.-----	• 0.01	• • 0.05
Silver.-----	• 0.05	-----
Sulfate.-----	250	• 250
Total solids.-----	500	• 1500
Zinc.-----	5.0	• 5.0
Radiological, pc/liter:		
Radium-226.-----	• 3	-----
Alpha emitters.-----	-----	• • 1
Strontium-90.-----	• 10	-----
Beta emitters.-----	• 1000	• • 10

- WHO European Standards of 1961.
- WHO International Standards of 1958.
- Mandatory. Others are recommended by USPHS.

Figure 15-14
Municipal Drinking Water Standards in Current Use
(After McKee⁽⁵¹⁾)

Biological quality was of particular concern to the Panel. It was felt strongly that, however rigorous pre-flight testing was, there would still be a prospect of introducing potentially harmful organisms into the supposedly pure-water side of the recovery system during takedown operations or by adventitious circumstances not encountered during testing. Accordingly, it was the strong recommendation of the Panel that any recovery system include a positive sterilizing procedure at some point following the phase separation step, even though the unit might be capable of producing a near sterile water under optimal conditions without such a procedure.

The Panel could think of no method except heat treatment, to pasteurization temperatures at least, that it considered acceptable; yet it did not want to exclude other methods of treatment, if they were available or could be devised, that would be as universally and reliably lethal to all forms of microbial life as heat treatment.

Table 15-15 presents the recommended standards for physical properties:

Table 15-15

Comparative Physical Properties Limits for Water Purity in Spacecraft

Test	NAS-NRC for Spacecraft (61)	Municipal USPHS (103)
1. Turbidity (Jackson Units)	not to exceed 10	5
2. Color (platinum-cobalt units)	not to exceed 15	15
3. Taste	none objectionable	same
4. Odor	none objectionable	maximum threshold No.3
5. Foaming	none persistent more than 15 seconds	—

Palatability and aesthetic acceptability are considered very important characteristics for water supplies in space flight. The severe stresses of a long space voyage in closely confined quarters should not be increased by any objectionable appearance or flavor in the water supply. Moreover, lack of adequate quality in these respects will tend to discourage normal intake of water and thus will decrease health and vigor below the optimal level.

Since the standards for taste and odor are subjective to some extent as a result of variations in individual sensitivity and experience, it is recommended that, if feasible, final evaluation of recovery systems for these properties be done by persons expected to participate in the space flights.

Recommended upper limits for chemical constituents in spacecraft water supplies (milligrams per liter) are given in Table 15-16 (61).

Some of the recommended standards for chemical quality have been based primarily on the adverse sensory properties that would be imparted to water by concentrations in excess of the limits. Those for chloride, copper sulfate and total solids fall in this category. All are well below levels at which harmful physiological effects would be experienced. It was felt unnecessary to set

Table 15-16

Recommended Upper Limits for Chemical Constituents in Spacecraft Water Supplies

	NAS-NRC for Spacecraft (48)	U.S.P.H.S. (103)	W.H.O. (115)
Arsenic	0.5	0.005	0.2
Barium	2.0	1.0	—
Boron	5.0	—	—
Cadmium	0.05	0.01	0.05
Chemical Oxygen Demand (dichromate method)	100.0	—	—
Chloride	450.0	250.0	350.0
Chromium (hexavalent)	0.05	0.05	0.05
Copper	3.0	1.0	3.0
Fluoride	2.0	1.6-3.4	1.5
Lead	0.2	0.05	0.1
Nitrate and Nitrite (as Nitrogen)	10.0	—	—
Nitrate, as No.3	—	45.0	50.0
Selenium	0.05	0.01	0.05
Silver	0.5	0.05	—
Sulfate	250.0	250.0	250.0
Total Solids	1000.0	—	—

specific limits for iron and manganese because undesirable concentrations of these materials would be manifest in unacceptable color or turbidity.

The limits for arsenic, barium, boron, cadmium, hexavalent chromium, fluoride, lead, nitrate and nitrite, selenium and silver have been based on potential toxic or adverse physiologic effects. The recommended limits are in many instances greater than those of the PHS drinking water standards, but they are considered well within limits of safety for consumption by healthy adults for periods of three years. The standard for Chemical Oxygen Demand (dichromate) is included to guard against excessive carry-over of organic matter in recovery systems utilizing urine or feces as sources of water. Virtually nothing is known about the possible build-up of toxic, perhaps volatile, organic materials in water that has been recycled many times through the human system.

The Panel recognized that there are many other toxic inorganic or organic substances which might, in special circumstances have some likelihood of occurrence in the water treated in space recovery systems. Examples are substances entrained from the cabin atmosphere in condensate water. They felt unable, however, to list all possible substances that might be encountered and considered it unrealistic to establish standards for hypothetical hazards. Accordingly, the list of chemical standards may be incomplete and may need supplementation if there are possibilities of toxic substances from unusual materials of construction or from substances employed in other parts of the operation of the space vehicle. Whenever possible, the Panel felt, control over such materials should be maintained by preventing their entrance into the spacecraft.

New techniques for rapidly monitoring total solids, total organic carbon, chemical oxygen demand, and other factors, are under development (21, 83 84, 91).

Biological requirements were also specified by the NAS-NRC (61). A number of features peculiar to the design and operation of water-recovery systems for space travel make the normal coliform tests used for municipal supplies of little value and increase the importance of the total count of microorganisms as a measure of microbiological quality of water. In systems regenerating water solely from urine, wash waters and condensate water, coliforms will not be a particularly reliable method for indicating extent of microbiological contamination. Moreover, recirculation of typical enteric organisms from discharges of the few individuals concerned in a space flight is not likely to be the major hygienic problem even when the recovery system may utilize fecal matter as well as other sources of water for raw material.

Of great concern, on the other hand, is the potential multiplication of microorganisms in any part of the recovery system accompanied by production of toxic metabolites such as endotoxins or exotoxins. Accumulation of organic and inorganic materials in the water-recovery system as a result of continual recycling may well create a suitable nutrient medium for such growth, particularly in filters or columns of absorbent. For example, spores of Clostridium botulinum are found not uncommonly in the human intestinal tract. If these spores, normally harmless on ingestion, are seeded on a filter or absorbent or in interstices where nutrient materials may accumulate and low redox potentials may be produced, then they could vegetate readily and produce their potent toxin. Traces of this in the final product water would be disastrous. A similar situation would result from the growth of Staphylococcus species and production of their enterotoxin. Another possible consequence of recycling is the accumulation of relatively nonpathogenic organisms such as Aerobacter aerogenes, Pseudomonas aeruginosa and numerous types of fungal spores. Relatively large numbers of such organisms may overwhelm the normal tolerance of man to ingestion or inhalation of small numbers of them, resulting in acute gastroenteritis or pulmonary disease. In addition, ear infections may be caused by Pseudomonas and by fungi, such as Aspergillus. Moreover, some mycoplasma (PPLO) and viruses are excreted in urine or feces. Other viruses of respiratory types may be concentrated in cabin condensate. While such agents, particularly the viruses, would not be expected to increase in the absence of viable tissue cells, positive control of them should be demonstrated for any water-recovery system.

Because of the diverse natures and modes of hazard of possible biological contaminants in water-recovery systems for space use, the Panel found no justification for the establishment of standards based on individual types of microorganisms. It was considered that the goal should be essential sterility and that total counts of aerobic, facultative and anaerobic organisms would be the best indications of attainment of this condition. A maximum of 10 viable microorganisms per milliliter was considered to be a realistic criterion for "essential sterility." It was considered essential, moreover, that this criterion of essential sterility be applied to all parts of the recovery system beyond the initial phase separation step and not simply to the finished product water. The Panel felt strongly that some positive form of sterilization was needed at some point in the recovery-storage-delivery system immediately after phase

separation. In addition it was felt that there should be provision for periodic heat treatment of the subsequent portions of the system to forestall hazards of possible bacterial or fungal growth.

For biological standards of drinking water for space use, the Panel specifically recommends that aliquots of the water, cultured separately for total aerobic organisms, total anaerobic organisms and total cytopathic viruses, yield no more than a sum total of 10 organisms per ml.

The latest methods for the examination of water and waste water have recently been reviewed and are applicable to physical and chemical analysis of spacecraft water supplies (3). In the case of microbiological quality, the following methodology was recommended by the NAS-NRC (61). To examine for total aerobic microorganisms 10-ml samples should be filtered through 0.45 micron membrane filters, the membranes placed in sterile petri dishes on pads moistened with trypticase soy broth or on plates of trypticase soy agar and the dishes incubated for 7 days at 35°C, followed by counting of the total colonies produced. A similar procedure should be followed for total anaerobic organisms except that incubation is to be carried out under anaerobic conditions.

To test for common viral agents, the filtrates from the aerobic and anaerobic samples should be concentrated in an ultracentrifuge and the pelleted material tested on suitable tissue cultures for cytopathic effects. Suitable tissue cultures can be selected on the basis of studies made with the raw fluid prior to its submission to the recovery process. It was also recommended that the recovery system be challenged with a large inoculum of an identifiable cytopathogenic virus during performance testing when the resulting product water is not to be consumed and that its elimination from the product water be demonstrated by the foregoing techniques.

Full monitoring of biological quality should be maintained at all stages of evaluation of water quality from recovery systems where this is feasible. When full monitoring cannot be maintained, maintenance of the standard for total aerobic and anaerobic counts together is considered satisfactory and when monitoring must be even more restricted than this, maintenance of the standard in terms of total aerobic count alone is suitable. In the last instance, membrane filter kits can be used to monitor aerobic organisms during flight. Of all the methods developed for rapid analysis of organisms in water, only the luciferin luciferase system has approached within an order of magnitude the requirement of detecting 10 organisms/ml (45, 91).

Water from fuel cells and from several systems of urine recovery has been found to be satisfactory for human consumption (11, 48, 54, 55, 56, 66, 69, 78, 91, 95, 105, 116). However, the contaminants exceed the standards set for municipal water supplies. A detailed compilation of the analytical results of water reclaimed mainly from urine and chamber atmosphere, including any chemical and physical treatment of source and/or product materials was used directly in the following summary (55, 91). These data are of value in setting human standards and in predicting the suitability of using the water for physico-chemical work in space laboratories. A synopsis of the results of 146 tests on water reclaimed from urine by some representative techniques is shown in Table 15-17a. These include membrane electrodialysis, in which the urine was

Table 15-17

Reclamation of Water from Various Sources in Space Cabin Simulation
(After Slonim et al⁽⁹¹⁾)

a. Analyses of Water Reclaimed from Urine by Various Techniques

Constituent	Reclamation Technique				
	Membrane Electrodialysis	Thermoelectric Distillation	Ultrafiltration	Vacuum Distillation	Vapor Compression
pH	6.3-7.7	6.2-9.0	7.0-8.4	4.9-9.7	6.8-10.1
Conductivity*	182-3500	210-1080	1800**	41-1750	—
Color†	—	<5-20	—	<5-5	<5-5
Turbidity†	<25->25	<25**	<25->25	0**	<25**
Odor†	—	0**	—	+**	1.6-111
<i>values in mg/l:</i>					
Tot. Hardness‡	—	4-116	10-48	<1-484	2-18
Tot. Alkalinity‡	—	56-414	100-174	16-350	16-120
COD	36-2300	<1-630	16-2100	17-2045	18-730
Tot. Carbon (Org.)	7.8-985	1-362	—	<0.5-790	—
Urea	2-300	<0.1-350	214**	0-120	—
ABS	—	<0.02-1.2	0.03**	—	<0.01-0.15
Calcium	—	1.6-48	8.8**	<1-92	0.08-4.8
Magnesium	—	0.5-13	4.3**	<0.3-62	0.12-<2
Sodium	12-495	2-330	56-212	<1-170	0.5-78
Potassium	9-250	1.4-100	17-269	<0.2-200	<0.1-19
Arsenic	0.01-0.16	<0.01-0.32	0.02-0.23	<0.01-0.02	<0.01-0.03
Ammonia (NH ₃ /N)	2.5-59	12-100	25-95	0.1-78	0-47
Sulfate	15-100	<1-205	60-150	<1-100	<1-176
Chloride	13-530	1.5-110	144-290	<1-460	<1-21
Nitrate (NO ₃ /N)	<0.1-24	<0.1-2.8	<0.1-350	<0.1-1.1	<0.01-0.8
Tot. Phosphate	<0.01-240	<0.01-21	<0.01-44	<0.05-23	<0.01-1.2
<i>values in µg/l:</i>					
Zinc	5-104	<3-165	<3-12	<5-55	<0.7-26
Cadmium	<10-<20	<1-30	<3-<10	<5-14	<0.3-<10
Boron	19-256	1-200	3-21	<5-105	6-880
Phosphorus	24->1000	60->1000	<5-<15	<20-500	<5->1000
Iron	4->800	2-390	<2-21	<3-20	<0.3->500
Molybdenum	<4-60	<5-78	<5-<10	<5-425	<1-18
Manganese	<1-16	<0.5-53	0.8-<3	<2.5-64	<0.1-11
Aluminum	<3-760	43->1000	<13-75	<10-75	50-4000
Beryllium	<0.02-<0.05	<0.01-<0.14	<0.03**	<0.03-<0.09	<0.01-<0.05
Copper	<2-39	<0.9-205	<2**	<3-11	0.8-24
Silver	<0.5-6	<0.5-20	<0.3-<0.5	<0.5-5	<0.1-<0.5
Nickel	<2-23	<3-13	<3-<5	<5-17	<0.3-21.5
Cobalt	<3-<21	<3-<14	<3-<5	<5-<12	<0.3-<5
Lead	<5-<20	<5-<18	5-<10	<10-490	<0.6-<5
Chromium	<1-105	<1-65	<1-<3	<2.5-15	<0.5-23
Vanadium	<13-<40	<5-<20	<5-<10	<10-<15	<0.7-<10
Barium	<1-75	1-114	5-6	<1-75	0.1-47
Strontium	<1-11	<1-179	<1-27	<1-165	0.3-20
Mercury	<30-560	15-250	<20-<25	<50**	<20-115
Number of Samples:	24	70	4	21	27

Range of values include results of any chemical or physical treatment during processing of water. Techniques are briefly explained in text.

* Values are expressed in micromhos per centimeter (µmhos/cm).

† Color - PtCl₆ units; Turbidity - Jackson units; Odor - Threshold odor numbers

‡ Values are expressed as amount of CaCO₃

** Denotes only a few samples were tested for constituent.

+ Trace of odor present.

(From the data of Metzger et al⁽⁵⁵⁾)

Table 15-17 (continued)

b. Analyses of Water Reclaimed from Chamber Atmosphere

Constituent	Unfiltered Condensate	Filtered Condensate
pH	5.6-7.5	6.8-7.6
Conductivity	142-660	310-600
Color	<5-40	<5-20
Turbidity	<25->25	—
Odor	0-38	—
<i>values in mg/l:</i>		
Tot. Hardness	<1-100	6-40
Tot. Alkalinity	44-234	110-192
COD	130-2300	43-350
Tot. Carbon (Org.)	26-590	15-87
Urea	0-5	<0.1
ABS	<0.02-0.17	—
Calcium	<1-18	—
Magnesium	<0.1-14	—
Sodium	<0.5-21	1.5-70
Potassium	<0.5-22	<1-16
Arenic	<0.01	<0.01-0.08
Ammonia (NH ₃ /N)	15-200	5-49
Sulfate	<1-18	1-150
Chloride	<1-50	<1-31
Nitrate (NO ₃ /N)	<0.1-1.6	<0.1-0.6
Tot. Phosphate	<0.01-2	<0.05
<i>values in µg/l:</i>		
Zinc	5-1020	<8-35
Cadmium	<10-200	<8-10
Boron	5->340	47-300
Phosphorus	<10-388	30-450
Iron	4-290	31-235
Molybdenum	<5-110	<10
Manganese	<1-197	1.5-18
Aluminum	<3-900	<13-750
Beryllium	<0.03-<0.05	<0.03
Copper	<2->250	2-21
Silver	<0.3-2	<0.5-4
Nickel	<3-20	<5-23
Cobalt	<3-<5	<5
Lead	<5-105	<10-10
Chromium	<1-28	<3-35
Vanadium	<5-<20	<10
Barium	33->500	19->50
Strontium	<1-33	<2-43
Mercury	<20-80	—
Number of Samples:	22	19

Dehumidification of the atmosphere was accomplished during a four-man experiment in the AMRL Life Support System Evaluator. The filtered condensate was produced by passage through activated carbon and two membrane filters (0.15 micron).

Legend - Same as Table 15-17a

(From the data of London and West⁽⁴⁷⁾)

Table 15-17 (continued)

c. Analyses of Water Produced from Different Fuel Cells

Constituent	Polystyrene-type Membrane	KOH-saturated Membrane
pH	2.8-3.6	6.7-11.5
Conductivity	345-4000	8.3-930
Color	5-45	0-29
Turbidity	0-7	0-7
Color	0-*	0-*
<i>values in mg/l:</i>		
Tot. Hardness	8-12**	—
Total Solids	120->1000	<10-424
COD	200-270**	—
Tot. Carbon (Org.)	40-89**	—
Urea	<0.1**	—
ABS	<0.02**	—
Phenols	0.01-0.4	—
Ammonia (NH ₃ /N)	0.5-2.8	0.1-5.6
Sulfate	3.5-35	1-2.5
Chloride	3.5-9.3	0.8-3.8
Chlorine	—	0**
Nitrate (NO ₃ /N)	1.2-2.5	1.5**
<i>values in µg/l:</i>		
Zinc	85-190**	—
Cadmium	<10-<11**	—
Boron	50-85**	—
Phosphorus	200-450**	—
Iron	59-290	0-70
Molybdenum	<5-<6**	—
Manganese	0-450	150-750
Aluminum	105-170**	—
Beryllium	<0.03**	—
Copper	2.5-135**	—
Silver	<0.5-4.5**	—
Nickel	<5-12**	—
Cobalt	<5-<6**	—
Lead	<10-<11**	—
Chromium	<3-6.1**	—
Vanadium	<10-<11**	—
Barium	3-18.5**	—
Strontium	<1-<2**	—
Mercury	100**	—
Number of Samples:	10	4

Legend - Same as Table 15-17a

(From the data of London and West ⁽⁴⁷⁾)

Table 15-17 (continued)

d. Bacterial Analyses of Water Produced by Various Sources

Sample	Bacteria/ml
Urine, raw (pooled and stored)	$3 \times 10^3 - 20.5 \times 10^6$
Water Reclaimed from Urine	
Compr. Dist.—Absorp. Filtr. (CDAF)	$18 \times 10^6 \dagger$
CDAF + Pall Filter	Neg - 6.5×10^6
Electrodialysis + Pall Filter	Neg - 32×10^6
Electro Process	Neg - 123×10^6
Electro Process + Pall Filter	Neg - 2×10^4
Electro Process + CDAF	Neg - 22×10^6
Membrane Permeation	$7 \times 10^3 - 24 \times 10^3$
Thermoelectric Distillation	$44 \times 10^6 - 91 \times 10^6$
Thermoelectric + Pall Filter	Neg - 103×10^6
Ultrafiltration	Neg - 73×10^7
Water Reclaimed from Chamber Atmosphere	
Unfiltered Condensate	$2 \times 10^3 - 8 \times 10^6$
Condensate + Pall Filter	Neg - 73×10^7
Water Produced from Fuel Cells	
Polystyrene-type Membrane*	Neg - $>10^7 \dagger$
KOH-saturated Membrane	Neg†

* Fresh water samples from this process only were not available; all other water samples were analyzed immediately upon collection.

† Three or less samples were analyzed.

‡ Only one of eight samples was contaminated.

(From the data of London and West⁽⁴⁷⁾)

pretreated with oxalic acid and silver nitrate and then filtered through activated carbon; thermoelectric distillation, in which the urine was either pretreated with trimethyl nitromethane and also carbon-filtered, treated with iodine, treated with chromate and sulfuric acid, or not treated at all; ultrafiltration, in which the urine was pretreated with urease and filtered, with citric acid added to the filtrate; vacuum distillation, in which the urine was untreated or passed over a low temperature catalyst; and vapor compression, in which the urine was untreated, filtered through a membrane, or pretreated with merthiolate and carbon-filtered. It can be seen that seven chemical constituents (ABS, As, Cl, Cr, Fe, Pb and NO_3) plus all three physical constituents (color, turbidity and odor) in only these five processes exceed the 1962 USPHS threshold values.

The results of 41 analyses on dehumidification water obtained during a four-man experiment in the AMRL Evaluator are synopsized in Table 15-16b. (91) In addition to all three physical characteristics, four chemicals (Ba, Cd, Pb and Mn) exceed the 1962 USPHS levels. Filtering the condensate through activated carbon plus two 0.15 micron filters improved the quality, but still the organic content remained high although less than the unfiltered samples. The levels for total dissolved solids (TDS) reported for urine and condensate (55) were not tabulated here, since it was noticed that in samples of high organic content, losses of volatile constituents by the direct heat evaporation method were very large resulting in lower values of TDS in many cases than some of the components present; nevertheless, both urine and condensate showed very large TDS levels exceeding the 1962 USPHS and 1964 Aerospace Threshold Limits. (89). Other workers (106) reported a high level for copper in their chamber condensate; the level of 2 mg/l Cu exceeds also the 1962 threshold value. They

reported also other high values (up to 4 mg/l) for Ca, Si and Zn in their condensate and lower values (0.2 to 2 mg/l) for Al, Cr, Fe and Ti.

The results of analyses of 14 samples from two different fuel cells are shown in Table 15-17c. For the first time, a new test for total solids, which includes dissolved and suspended matter, was applied to some of the samples. (86). It can be seen that color, turbidity, manganese, phenols and total solids exceed the 1962 USPHS levels. In addition, a fluoride content of 2 mg/l, which exceeds the public health limit, was reported in water samples taken from one of the polystyrene-type fuel cells used in a human evaluation experiment (48). The organic content of water from this type of fuel cell was very high at times, as measured by both COD and total organic carbon.

In summary only three of a total of 20 chemical constituents listed by USPHS were not reported above, viz., carbon chloroform extract (CCE) cyanide (CN) and selenium (Se) for reasons outlined in Reference (91). Excluding CCE and CN, of 18 chemical constituents analyzed in all, 14 have been shown to exceed the 1962 USPHS threshold levels; only selenium, silver, sulfate and zinc have been lower than the public health limit. Moreover, the three physical characteristics of color, turbidity and odor have exceeded also the USPHS levels in case of almost all processes. Hydroquinones from fuel cells still remain a problem (32).

The bacterial content of the water samples taken from all three major water sources are shown in Table 15-17d. With the exception of raw urine and samples taken from the polystyrene-type fuel cell, all samples were collected aseptically and analyzed immediately. The highly positive results obtained with water from urine and chamber atmosphere reflect more the lack of proper biological controls than the failure of the technique to produce biologically clean water. For, whenever special care was taken with the technique (e.g., cleaning apparatus prior to test, proper handling of waste sample, etc.) the water was negative for bacteria in most cases. A more detailed analysis and the significance of these bacteriological data is available (47).

The purity standards of Tables 15-15 and 16 take into account the levels of contaminants found in Table 15-17. Reduction of these levels will impose an unrealistic design problem. In view of lack of clinical problems arising after ingestion of these reclaimed waters by humans, these water standards appear acceptable.

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16. ANTHROPOMETRY AND TEMPORO-SPATIAL ENVIRONMENT

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16. ANTHROPOMETRY AND TEMPORO-SPATIAL ENVIRONMENT

The management of workspace, clothing and time elements in space operations is a major factor in optimizing crew comfort and efficiency. The anthropometric sizing of the astronaut population will be used whenever these data are available. Alteration of optimum workspace by zero gravity has already been covered under zero gravity in Acceleration (No. 7). Confinement and biorhythmic factors will complete the section.

ANTHROPOMETRIC FACTORS IN WORKSPACE ANALYSIS

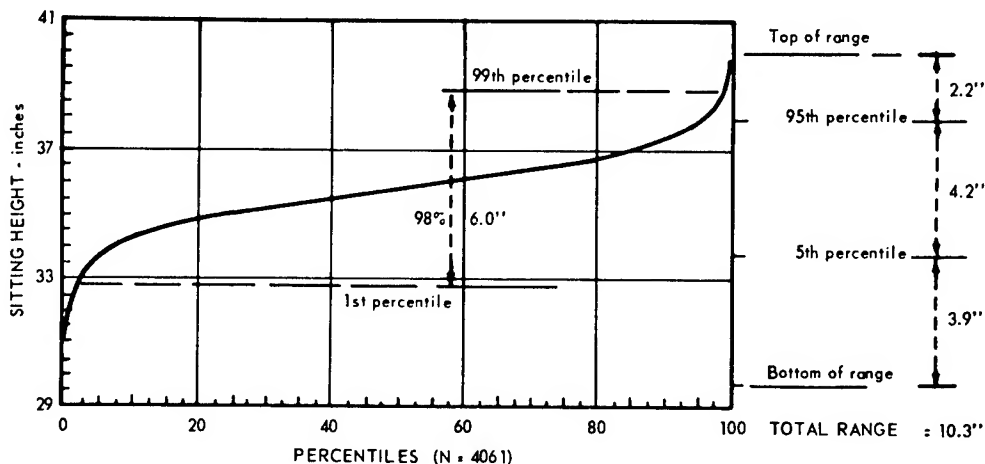
Several reviews are available of anthropometric factors in engineering design (71, 72, 145, 163, 164, 165, 213, 224, 234, 241, 246, 263, 294, 310). These cover static and dynamic body dimensions of the general population, as well as specific military groups. These may be used in the design of the appropriate ground based- as well as flight equipment whenever the specific dimensions of the astronaut group are not critical.

Those aspects of spacecraft design that are related to the anthropological (or physical) characteristics and the performance of the crew include: (25, 213, 224, 233, 234, 246)

- Design of protective clothing and portable life support systems (fit, mobility, task performance considerations) (129, 131, 232, 236, 243, 245, 246, 247, 331, 332, 333, 336, 371)
- Layout of the workspace in the spacecraft cabins (89, 129, 131, 232, 233, 236, 243, 245, 246, 247, 331, 333, 373)
- Design of the occupancy and restraint systems (fit, mobility, and support considerations (129, 131, 232, 246, 331, 332, 333, 336)
- Selection and design of displays and controls (88, 129, 130, 131, 160, 213, 224, 232, 233, 234, 243, 245, 247, 331, 332, 333, 336)
- Design of the equipment for maintainability (102, 333)
- Design of training equipment (to support crew performance) (130, 232, 332, 333, 336)
- Safety and hazard standards related to the spacecraft (123, 243, 245, 246, 247, 330, 331, 332, 333, 336)

Human Dimensions

Most of the anthropometric data are presented as percentiles of the population distribution. The use of percentile values as opposed to average or mean values is illustrated in Figure 16-1. In the charts presented in this section, whenever possible the size and composition of the population sample from which the data are derived are indicated (72).



The meaning of percentile. Percentiles comprise the 100 equal parts into which the entire range of values is divided for any given dimension. As an illustration, sitting heights of a large sample of men were measured and the values distributed graphically into the 100 percentiles as shown in the graph above.

The designer should design according to the concept of "design limits" or "range of accommodation." This concept, exemplified in the graph, involves the evaluation of percentile ranges. Note that the variability of the extreme 10% (the largest 5% and the smallest 5% combined) exceeds the variability of the central 90%, and so does the variability of the extreme 2% (largest 1% and smallest 1% combined). By proper analysis of the data on the using population, the designer can efficiently provide precisely the adjustability needed for any desired segment of the population.

Figure 16-1

The Use of Percentile Values in Anthropometry

(After Hertzberg and Clauser (164))

Human dimensions are measured in a standardized manner. Such standardization is critical if data from one population are to be compared with data from a different population. One must know the position of the body, the points on the body surface from which measurements are made, and whether the body was nude or clothed. Sketches accompany many of the charts to indicate how the measurements were taken.

In choosing design values from tables of anthropometric or biomechanical data, the engineer should select that value which will accommodate the maximum practicable percentage of the potential user population. For example, an access hatch should be large enough for the largest man to pass through; a switch for a panel to be operated by a seated, restrained operator should be

located at a distance no farther than that which the man with the shortest arm can efficiently reach to actuate the switch. A control should not require more force than the weakest man who is to use the equipment can be expected to apply, yet the control should be able to withstand more force than the strongest man can be expected to apply under normal conditions. For astronauts it is vital that the entire range be accommodated, but for non-astronauts using ground-based equipment, 95% or -- if space is critical -- 90% of the range may suffice. Furthermore, the principle of mock-up trials, using subjects who are physically representative of the using population, wearing typical outfits, and performing simulated tasks, should be used before final decisions on design are made. For ground-based operations, anthropometric data are required on the general population. The basic body dimensions of a generalized U. S. male population is noted in Figure 16-2. The U. S. National Health Examination Survey, conducted in 1962-64, gives 10 key dimensions for a truly representative sample of the U. S. population. Data are presented by age group (18-24, 25-29, etc., to age 79) covering the total population (71, 334).

Anthropometric data are required for design of equipment used in military aircraft supporting launch, recovery and in-flight monitoring operations. Dimensions of the USAF flying personnel are noted in Figure 16-3. Correlations between the dimensions of this population are available (164). Table 16-4 covers the overall head, body, and limb measurements of the astronaut population. The body dimensions of from 3 to 38 astronauts were used to establish means, standard deviations, and ranges (94).

The need for biomechanical data regarding the center of gravity (CG) and moments of inertia of the human body and body segments arises in several fields of application. Such data are useful in determining the stability and angular acceleration of equipment occupied or operated by persons in various postural attitudes; in the design of seats, particularly aircraft ejection seats and fastening devices; in dummy construction; in assessing the ability to apply torque while in the weightless state and the consequences of such application; and in the study of human biomechanics. An excellent review of the techniques of measurement is available (84). Data in the older literature (35, 201) have been updated by more recent studies (22, 23, 77).

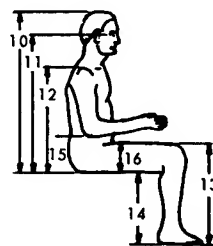
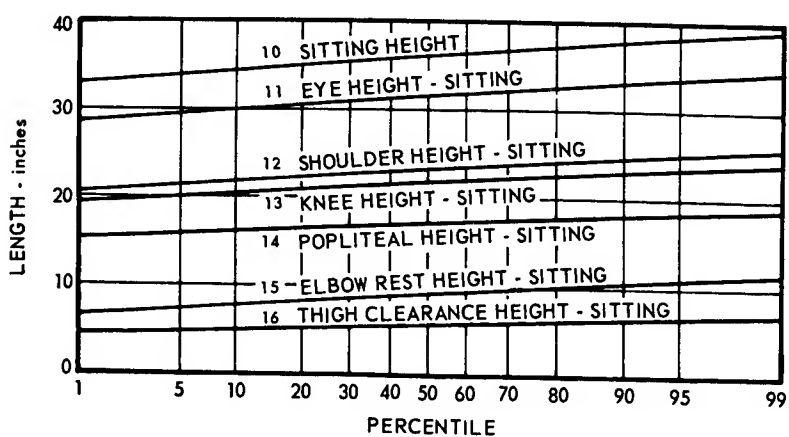
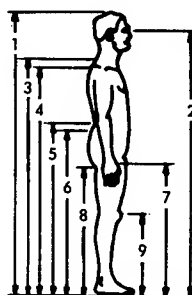
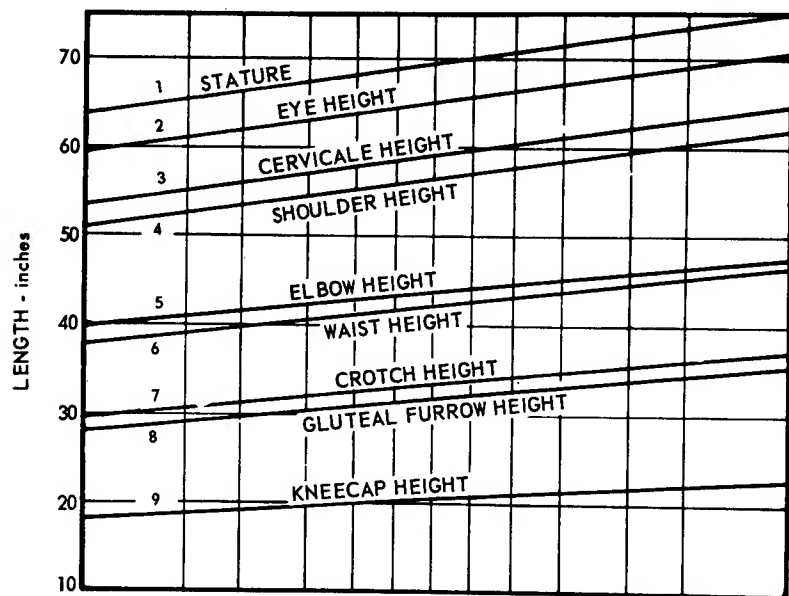
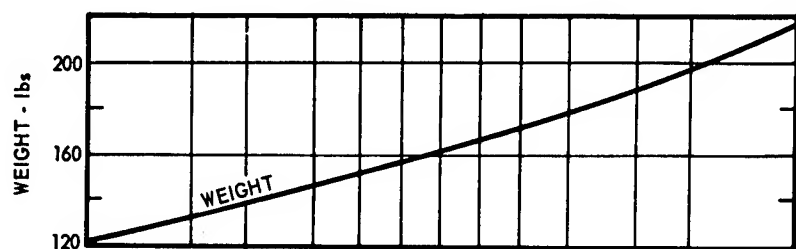
Moment of inertia (I_{CG}) about the segment CG is equal to the product of segment mass and radius of gyration squared. Moment of inertia about a proximal joint center (I_0) is related to I_{CG} by the formula:

$$I_0 = I_{CG} + mD^2, \quad (1)$$

where m is the segment mass and D is the distance from the joint center to the CG. The moments of inertia of the segments can be determined by a free-swinging pendulum system. The segments were suspended from the proximal joint center, the oscillation period measured, and the moment of inertia determined by the relation:

$$I_0 = \frac{mgL}{4\pi^2 f^2} \quad (2)$$

where I_0 = moment of inertia about the point of suspension,
 m = mass of the segment (weight/g),



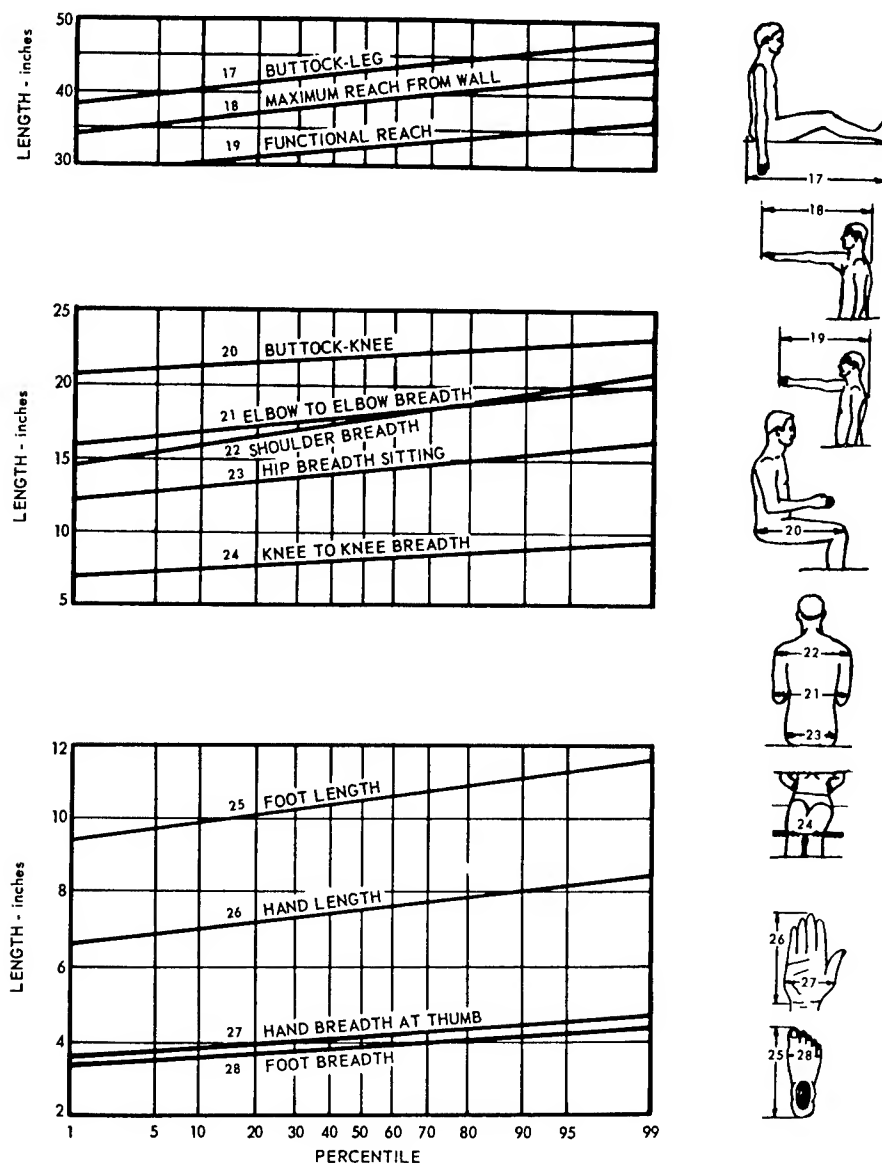
Body dimensions of a sample of approximately 4060 flying personnel of the U.S. Air Force.

Figure 16-3

Dimensions of Flying Personnel

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Figure 16-3 (continued)



Anthropometry of the Astronaut Population
(See end of table for description of non-standard measurements)*
(From the data of Feddersen and Reed(94))

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range		Mean	Std. Dev.	Range	
				Low	High			Low	High
1. Weight of Body	31	74.37	6.67	63.50	90.26	163.94	14.71	140.00	199.00
2. Height of Body, Erect	36	177.00	4.09	168.70	183.40	69.71	1.61	66.42	72.21
3. Height of Body, Normal	28	176.43	3.91	167.80	183.40	69.46	1.54	66.06	72.20
4. Height of Body, Sitting, Normal	28	92.41	2.58	87.70	97.90	36.38	1.02	34.53	38.54
5. Height of Eyes, Standing	27	164.03	5.24	151.70	178.00	64.58	2.06	59.72	70.08
6. Height of Eyes, Seated	24	80.73	2.93	74.20	85.20	31.78	1.15	29.21	33.54
7. Height to Tragion, Seated	17	79.10	2.30	74.20	82.80	31.14	0.91	29.21	32.60
8. Height to Cervical Level, Standing	28	152.98	7.15	145.50	185.40	60.23	2.82	57.28	72.99
9. Height to Cervical Level, Seated	21	65.88	2.92	58.30	70.00	25.94	1.15	22.95	27.56
10. Height to Right Mid-shoulder*	38	149.82	3.94	141.10	157.70	58.99	1.55	55.55	62.09
11. Height to Left Mid-shoulder*	38	150.01	3.95	142.20	158.00	59.06	1.56	55.98	62.20
12. Height to Right Shoulder	28	144.95	3.77	137.20	151.10	57.07	1.49	54.02	59.49
13. Height to Left Shoulder	28	145.24	3.78	136.80	151.30	57.18	1.49	53.86	59.57
14. Height to Acromion, Standing	28	144.25	3.74	136.60	151.20	56.79	1.47	53.78	59.53
15. Height to Acromion, Seated	24	59.96	2.26	55.30	64.00	23.61	0.89	21.77	25.20
16. Height to Nipple, Standing	28	129.11	4.20	120.80	142.20	50.83	1.65	47.56	55.98
17. Height to Armpit, Seated	10	45.23	3.54	40.60	50.20	17.81	1.39	15.98	19.77
18. Height to Elbow, Standing	3	106.60	3.92	103.50	111.00	41.97	1.54	40.75	43.70
19. Height to Elbow, Seated	18	24.06	2.83	19.20	28.00	9.47	1.11	7.56	11.02
20. Height to Wrist, Standing	3	83.30	3.83	80.00	87.50	32.80	1.50	31.50	34.45
21. Height to Knuckles, Standing	3	74.97	2.14	73.10	77.30	29.52	0.84	28.78	30.43
22. Height to Suprasternal Level, Standing	28	143.68	3.46	136.70	149.70	56.57	1.36	53.82	58.94
23. Height to Substernal Level, Standing	10	124.28	3.34	118.60	128.60	48.93	1.31	46.69	50.62
24. Height to Xiphoid Level, Standing	6	118.92	2.38	115.60	122.00	46.82	0.94	45.51	48.03
25. Height to 10th Rib	8	113.06	3.23	106.80	116.10	44.51	1.27	42.05	45.71

Table 16-4 (continued)

a. Overall Dimensions of the Head, Body, and Limbs of the Astronaut Population (continued)

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low High		Mean	Std. Dev.	Range Low High	
26. Height to Cristal Level	22	106.19	2.91	99.80 110.80		41.81	1.15	39.29 43.62	
27. Height to Trunk, Standing	18	165.81	4.91	158.30 173.70		65.28	1.93	62.32 68.39	
28. Height to Trunk, Seated	10	159.86	6.36	153.00 169.60		62.94	2.50	60.24 66.77	
29. Height to Waist*	28	107.03	2.52	101.40 110.90		42.14	0.99	39.92 43.66	
30. Length from Crown to Rump	24	96.11	2.47	91.80 100.40		37.84	0.97	36.14 39.53	
31. Height from Acromion to Vertex	3	37.43	1.23	36.40 38.80		14.74	0.48	14.33 15.28	
32. Height from Cervical Level to Vertex	24	25.85	1.20	23.20 28.00		10.18	0.47	9.13 11.02	
33. Height to Trochanteric Level	28	91.77	2.81	86.80 96.40		36.13	1.11	34.17 37.95	
34. Height to Crotch	38	83.12	2.48	78.20 87.60		32.72	0.98	30.79 34.49	
35. Height to Gluteal Furrow	11	80.18	2.53	76.40 84.00		31.57	1.00	30.08 33.07	
36. Height to Knee	21	55.54	1.58	51.80 58.00		21.87	0.62	20.39 22.83	
37. Height to Superior Kneecap Level	28	52.20	1.81	49.30 57.20		20.55	0.71	19.41 22.52	
38. Height to Center Knee Floor	28	49.79	2.20	47.20 58.00		19.60	0.87	18.58 22.83	
39. Height to Popliteal Position	18	43.14	2.01	38.50 47.60		16.98	0.79	15.16 18.74	
40. Height to Tibia	24	46.60	1.74	42.60 48.80		18.35	0.69	16.77 19.21	
41. Breadth from Forearm to Forearm	18	51.16	2.94	45.70 56.50		20.14	1.16	17.99 22.24	
42. Breadth from Elbow to Elbow	20	46.13	2.75	41.80 51.30		18.16	1.08	16.46 20.20	
43. Breadth from Knee to Knee	28	20.69	1.18	18.90 22.70		8.15	0.46	7.44 8.94	

b. Dimensions of the Head of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low High		Mean	Std. Dev.	Range Low High	
1. Length of Head	28	19.96	0.47	19.20 21.20		7.86	0.19	7.56 8.35	
2. Breadth of Head	28	15.55	0.57	14.50 17.30		6.12	0.22	5.71 6.81	
3. Circumference of Head	28	57.80	1.35	54.61 60.01		22.56	0.53	21.50 23.63	

Table 16-4 (continued)

b. Dimensions of the Head of the Astronaut Population (continued)	Measurements	Observations	Centimeters				Inches			
			Mean	Std. Dev.	Range		Mean	Std. Dev.	Range	
					Low	High			Low	High
4.	Height of Face, Total	25	11.94	0.64	10.80	13.30	4.70	0.25	4.25	5.24
5.	Height from Pupil to Vertex	27	11.51	1.36	9.40	14.70	4.53	0.54	3.70	5.79
6.	Height from Stomion to Vertex	18	18.32	1.31	16.40	21.30	7.21	0.52	6.46	8.39
7.	Height from Tragon to Vertex	25	13.09	0.64	11.90	14.40	5.15	0.25	4.69	5.68
8.	Length from Menton to Crinion	10	18.43	0.94	16.90	19.40	7.26	0.37	6.65	7.63
9.	Length from Menton to Subnasal	10	6.64	0.61	5.80	7.80	2.61	0.24	2.28	3.07
10.	Breadth from Ear to Ear	17	18.97	0.83	17.70	20.60	7.47	0.33	6.99	8.11
11.	Distance Between Pupils	18	6.33	0.31	5.70	7.00	2.49	0.12	2.24	2.76
12.	Depth from Nasal Root to Wall	13	19.95	0.38	19.30	20.50	7.85	0.15	7.60	8.07
13.	Depth from Pronasal Position to Wall	18	22.11	0.58	21.00	23.20	8.70	0.23	8.29	9.13
14.	Depth from Pupil to Wall	24	18.56	0.62	17.50	19.70	7.31	0.24	6.89	7.76
15.	Depth from External Canthus to Wall	6	17.97	0.41	17.40	18.60	7.07	0.16	6.85	7.32
16.	Depth from Tragon to Wall	18	9.82	0.78	8.60	11.10	3.87	0.31	3.39	4.37
17.	Breadth of Ear	18	3.74	0.25	3.30	4.10	1.47	0.10	1.23	1.61
18.	Length of Ear	18	6.56	0.47	5.10	7.10	2.58	0.19	2.01	2.80
19.	Length of Ear above Tragon	18	3.08	0.45	2.60	4.10	1.21	0.18	1.02	1.61
20.	Breadth of Nose	7	3.44	0.26	3.20	3.80	1.35	0.10	1.26	1.50
21.	Breadth of Nasal Root	7	1.51	0.24	1.30	2.00	0.59	0.09	0.51	0.79
22.	Length of Nose	14	5.16	0.27	4.70	5.60	2.03	0.11	1.85	2.20
23.	Diameter between Tragon	9	14.39	0.46	13.40	15.00	5.67	0.18	5.28	5.91
24.	Length of Bitragon-Coronal Arc	6	34.67	0.66	33.40	35.30	13.65	0.26	13.15	13.90
25.	Length of Bitragon-Crinion Arc	8	32.29	1.15	30.60	34.00	12.71	0.45	12.05	13.39
26.	Length of Bitragon-Inion Arc	6	28.93	1.16	27.70	30.60	11.39	0.46	10.91	12.05
27.	Length of Bitragon-Menton Arc	10	31.81	0.87	30.50	33.30	12.52	0.34	12.01	13.11

Table 16-4 (continued)

b. Dimensions of the Head of the Astronaut Population (continued)

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low	Range High	Mean	Std. Dev.	Range Low	Range High
28. Length of Bitragion-Sub-mandibular Arc	6	30.05	0.89	28.80	31.50	11.83	0.35	11.34	12.40
29. Length of Bitragion-Subnasal Arc	6	28.48	0.70	27.50	29.50	11.21	0.28	10.83	11.61
30. Breadth between Gonion	13	11.07	0.39	10.30	11.60	4.36	0.15	4.06	4.57
31. Bizygomatic Diameter between Zygomatic Bones	21	14.30	0.51	13.70	15.60	5.63	0.20	5.39	6.14
32. Length of Lips	18	5.33	0.39	4.60	6.10	2.10	0.15	1.81	2.40
33. Circumference of Neck	28	38.50	1.65	34.61	41.59	15.16	0.65	13.63	16.38
34. Length of Anterior Neck	28	10.31	1.14	7.62	12.70	4.06	0.45	3.00	5.00
35. Length of Posterior Neck	28	10.18	0.91	8.26	12.70	4.01	0.36	3.25	5.00
36. Depth from Larynx to Wall	3	16.40	1.10	15.30	17.50	6.46	0.43	6.02	6.89
37. Mid-Shoulder to Top of Head*	11	27.68	1.46	25.40	30.48	10.50	0.58	10.00	12.00

c. Dimensions of the Trunk and Torso of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low	Range High	Mean	Std. Dev.	Range Low	Range High
1. Breadth of Shoulders, Acromion	28	40.24	1.70	36.20	43.30	15.84	0.67	14.25	17.05
2. Breadth of Shoulders, Across Deltoids	28	47.54	3.79	35.80	52.70	18.72	1.49	14.09	20.75
3. Circumference of Shoulders	28	117.01	4.57	109.22	128.27	46.07	1.80	43.00	50.50
4. Breadth of Chest	28	32.46	2.12	28.70	38.10	12.78	0.83	11.30	15.00
5. Breadth of Chest, Bone	8	29.93	1.72	28.00	33.20	11.78	0.68	11.02	13.07
6. Breadth of Inter Scye	28	36.13	1.95	31.90	39.80	14.23	0.77	12.58	15.67
7. Breadth of Biacromial	28	40.83	1.80	37.60	44.80	16.07	0.71	14.80	17.64
8. Circumference of Chest at Scye	38	100.87	4.22	95.25	111.76	39.71	1.66	37.50	44.00

Table 16-4 (continued)

c. Dimensions of the Trunk and Torso of the Astronaut Population (continued)

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low High		Mean	Std. Dev.	Range Low High	
9. Circumference of Chest at Nipple	38	96.90	4.15	89.54 104.77		38.15	1.63	35.25 41.25	
10. Circumference of Right* Vertical Trunk	36	168.80	6.10	158.75 181.61		66.46	2.40	62.50 71.50	
11. Depth of Chest	28	24.03	1.64	21.30 27.50		9.46	0.65	8.39 10.83	
12. Breadth of Waist	28	30.34	1.65	27.60 33.60		11.94	0.65	10.87 13.23	
13. Diameter of Left Vertical Trunk*	38	66.17	2.35	62.00 70.50		26.05	0.93	24.41 27.76	
14. Diameter of Right Vertical Trunk*	38	66.30	2.35	61.40 70.20		26.10	0.92	24.17 27.64	
15. Width of Waist, Front	7	32.31	1.21	30.70 34.40		12.72	0.48	12.09 13.54	
16. Width of Waist, Back	7	39.04	1.97	37.00 42.00		15.37	0.78	14.57 16.54	
17. Depth of Waist	18	21.14	1.72	18.80 25.20		8.32	0.68	7.40 9.92	
18. Front Length of Waist*	28	38.07	2.17	34.29 42.55		14.99	0.86	13.50 16.75	
19. Back Length of Waist*	28	46.75	1.74	43.82 50.80		18.41	0.68	17.25 20.00	
20. Circumference of Waist	38	82.46	4.74	72.07 92.07		32.46	1.87	28.38 36.25	
21. Breadth of Hip	28	34.70	1.77	31.30 38.90		13.66	0.70	12.32 15.32	
22. Breadth of Hips, Seated	27	36.46	1.54	34.00 39.90		14.35	0.61	13.39 15.71	
23. Circumference of Buttocks*	38	96.19	4.31	90.17 109.22		37.87	1.40	35.50 43.00	
24. Breadth across Trochanters	22	33.04	1.31	31.30 35.70		13.01	0.52	12.32 14.06	
25. Breadth across Iliac Crest	22	28.45	1.29	26.70 31.30		11.20	0.51	10.51 12.32	
26. Length of Gluteal Arc*	28	28.70	1.49	24.77 31.43		11.30	0.59	9.75 12.38	
27. Length of Seat	10	47.75	1.58	46.20 51.00		18.80	0.62	18.19 20.08	
28. Length of Crotch*	28	70.18	3.60	63.18 76.87		27.63	1.42	24.88 30.25	

Table 16-4 (continued)

d. Dimensions of the Arms and Hands of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low High	Mean	Std. Dev.	Range Low High		
Arms									
1. Length from Acromion to Radiale	18	33.58	1.28	31.40 36.90	13.22	0.50	12.36 14.53		
2. Length from Shoulder to Elbow	28	36.82	1.19	34.70 39.90	14.50	0.44	13.66 15.71		
3. Length from Shoulder to Elbow Pivot	28	33.53	1.58	30.80 36.83	13.20	0.62	12.13 14.50		
4. Length of Forearm to Wrist	11	29.30	1.02	27.60 31.20	11.54	0.40	10.87 12.28		
5. Length of Forearm to Grip	23	35.40	1.07	33.30 37.00	13.94	0.42	13.11 14.57		
6. Length from Forearm to Hand	28	47.58	2.04	43.50 51.80	18.73	0.80	17.13 20.39		
7. Scye Circumference, Right*	38	46.37	2.17	42.23 50.80	18.26	0.85	16.63 20.00		
8. Scye Circumference, Left*	38	45.88	2.13	40.64 50.17	18.06	0.84	16.00 19.75		
9. Circumference of Axillary Arm	28	31.86	1.88	27.94 35.56	12.54	0.74	11.00 14.00		
10. Circumference of Upper Arm, Relaxed	17	30.49	1.82	26.50 32.60	12.00	0.72	10.43 12.83		
11. Circumference of Biceps, Flexed	28	33.66	1.99	29.21 38.10	13.25	0.78	11.50 15.00		
12. Breadth of Elbow	10	9.10	1.45	7.00 10.50	3.58	0.57	2.76 4.13		
13. Circumference of Elbow, Relaxed	9	28.21	1.37	26.30 30.40	11.10	0.54	10.35 11.97		
14. Circumference of Elbow, Flexed	28	32.21	1.87	29.21 37.15	12.68	0.74	11.50 14.63		
15. Circumference of Forearm, Relaxed	23	28.11	1.00	26.50 30.00	11.07	0.39	10.43 11.81		
16. Circumference of Forearm, Flexed	28	29.35	1.61	26.67 33.65	11.56	0.63	10.50 13.25		
17. Breadth of Wrist	28	5.95	0.22	5.60 6.60	2.34	0.09	2.20 2.60		
18. Length from Elbow Pivot to Wrist	28	27.29	1.10	25.40 29.53	10.75	0.43	10.00 11.63		
19. Circumference of Wrist	28	17.54	1.42	15.88 23.50	6.91	0.56	6.25 9.25		
20. Sleeve Inseam, Right*	27	48.38	2.80	36.20 52.39	19.05	1.10	14.25 20.63		
21. Span of Arms	37	180.37	4.55	171.13 188.60	71.01	1.79	67.38 74.25		

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Low	High	Mean	Std. Dev.	Low	High
Hands									
1. Length of Hand	25	18.98	1.28	14.30	21.60	7.47	0.50	5.63	8.50
2. Length from Wrist to Forefinger Tip	31	19.80	1.52	17.15	24.77	7.60	0.60	6.75	9.75
3. Breadth of Hand at Metacarpal	17	8.88	0.37	8.10	9.70	3.50	0.15	3.19	3.82
4. Breadth of Hand at Thumb	8	10.49	0.58	9.70	11.40	4.13	0.23	3.82	4.49
5. Circumference of Hand at Metacarpal-phalangeal Joint	33	21.18	2.99	5.90	24.79	8.37	1.18	2.13	9.75

e. Dimensions of the Legs and Feet of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Low	High	Mean	Std. Dev.	Low	High
Legs									
1. Length from Buttock to Knee	23	60.39	1.51	57.50	63.30	23.78	0.60	22.64	24.92
2. Height of Thigh, Seated	10	15.44	0.91	14.30	17.30	6.08	0.36	5.63	6.81
3. Circumference of Upper Thigh, Standing	28	57.94	4.89	52.39	77.15	22.81	1.93	20.63	30.38
4. Circumference of Mid-Thigh, Standing	28	53.62	2.79	50.14	61.50	21.11	1.10	19.75	24.25
5. Circumference of Lower Thigh, Standing	28	39.49	1.90	36.51	43.82	15.55	0.75	14.38	17.25
6. Circumference of Knee	28	39.52	1.54	37.14	42.86	15.56	0.61	14.63	16.88
7. Circumference of Calf	28	38.52	1.96	34.61	41.91	15.17	0.77	13.63	16.50
8. Circumference of Ankle	28	22.46	1.10	20.20	25.50	8.84	0.43	7.95	10.04
Feet									
1. Length of Right Foot, Standing	28	24.99	3.19	19.05	30.48	9.84	1.26	7.50	12.00
2. Length of Left Foot, Standing	28	24.95	3.12	19.05	31.75	9.82	1.23	7.50	12.50
3. Length of Foot, No Weight	15	26.43	1.05	24.80	28.50	10.41	0.41	9.76	11.22

Table 16-4 (continued)

e. Dimensions of the Legs and Feet of the Astronaut Population (continued)

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range		Mean	Std. Dev.	Range	
				Low	High			Low	High
4. Length of Instep, Right Foot	28	27.31	3.57	20.32	34.29	10.75	1.40	8.00	13.50
5. Length of Instep, Left Foot	28	26.49	3.03	22.86	31.75	10.43	1.19	9.00	12.50
6. Breadth of Foot, Standing	27	10.29	0.54	9.40	11.50	4.05	0.21	3.70	4.53
7. Breadth of Foot, No Weight	15	9.55	0.63	8.90	11.20	3.76	0.25	3.50	4.41
8. Breadth of Heel	10	6.81	0.26	6.40	7.20	2.68	0.10	2.52	2.83
9. Breadth of Heel, No Weight	15	6.25	0.35	5.50	6.90	2.46	0.14	2.17	2.72
10. Medial Malleolus Height	16	8.84	0.62	8.10	9.70	3.48	0.24	3.19	3.82
11. Lateral Malleolus Height	15	7.06	0.32	6.40	7.60	2.78	0.13	2.52	2.99
12. Circumference of Instep, Right Foot*	28	34.28	1.44	31.43	37.46	13.60	0.57	12.38	14.75
13. Circumference of Instep, Left Foot*	28	34.27	1.45	31.12	37.46	13.49	0.57	12.25	14.75

f. Dimensions of the Skinfolts of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range		Mean	Std. Dev.	Range	
				Low	High			Low	High
1. Subscapular	10	0.90	0.23	0.70	1.50	0.35	0.09	0.28	0.59
2. Juxta-Nipple	10	0.56	0.18	0.40	0.95	0.22	0.07	0.16	0.37
3. Mid-Axillary Line-Xiphoid	10	0.74	0.74	0.29	0.50	1.50	0.29	0.11	0.59
4. Triceps	10	0.71	0.17	0.40	1.00	0.28	0.07	0.16	0.39

g. Reach with the Arm (Functional Arm Reach) of the Astronaut Population

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range		Mean	Std. Dev.	Range	
				Low	High			Low	High
1. Entire Arm	24	79.83	3.20	73.90	87.50	31.43	1.26	29.10	34.45
2. Forearm	9	41.84	1.24	39.00	43.10	16.47	0.49	15.35	16.97
3. Length of Extended Arm*	11	72.13	2.20	69.20	74.00	28.39	0.87	27.25	29.13

*Description of Non-Standard Measurements

- | | |
|---|--|
| 1. Back Length of Waist | Distance from waist back mark to cervical prominence. |
| 2. Circumference of Buttocks | Measured at point of maximum circumference. |
| 3. Extended Arm Length | Distance from apex of armpit (equidistant between anterior and posterior folds) along arms (extended laterally and horizontally) to the tip of forefinger. |
| 4. Front Length of Waist | Distance from waist front mark to the bottom of sternal notch. |
| 5. Instep Circumference | Circumference of foot measured with poles at apex of heel and dorsum of foot above peak of arch. |
| 6. Length of Crotch | Distance measured along the skin from the anterior waistline through the crotch to the posterior waistline. |
| 7. Length of Gluteal Arc | Distance measured along the skin from the top of buttock fold, craniad, to posterior waist point. |
| 8. Mid-Shoulder | Point on top of shoulder at 4" distance from the dorsal cervical prominence. |
| 9. Mid-Shoulder to Top of Head | Vertical distance from the horizontal line at mid-shoulder point to horizontal line at top of head. |
| 10. Scye Circumference | Circumference of shoulder measured along a line extending vertically from the apex of the armpit concavity. |
| 11. Sleeve Inseam | Distance from apex of armpit to first joint of wrist. |
| 12. Vertical Trunk Diameter and Circumference | Distance of the straight-line projection from mid-shoulder point to apex of crotch and the circumference along this line (following the skin contours). |
| 13. Waist Level | Measured at the level of the iliac crest. |

L = distance from the CG to the suspension point,

f = frequency of oscillation and

g = acceleration of gravity (980 cm/sec^2);

and
$$I_{CG} = I_0 - mL^2, \quad (3)$$

where I_{CG} = moment of inertia about the CG.

A shift in whole body moment of inertia because of changes in posture or movement of limbs will be equivalent to the algebraic term of the individual segment changes in moment of inertia about the axis of rotation. The contribution of each segment to total moment of inertia is determined by the equation:

$$I_{Total} = (I_{CG} + mx^2), \quad (4)$$

where I_{CG} = moment of inertia about segment CG

m = mass of the segment,

x = distance of the segment CG from the axis of rotation.

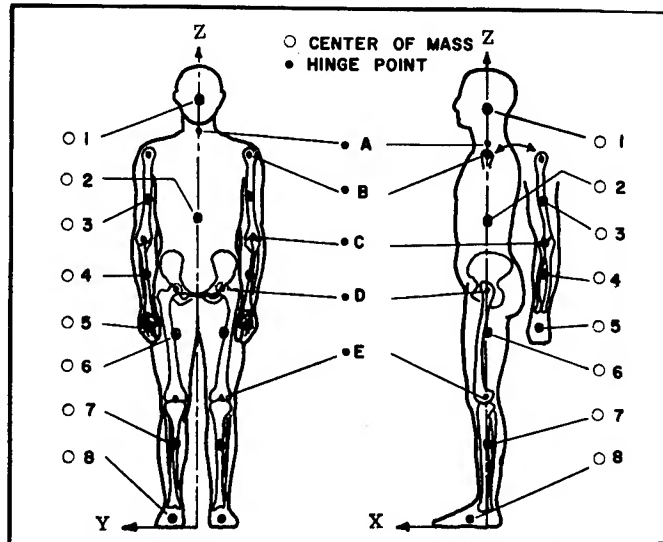
Consequently the change in I_{Total} is the difference between the sum of mx^2 before and after change in posture.

Table 16-5a shows diagrammatically the hinge points and centers of mass of the body segments. Table 16-5b gives the coordinates of these points. Table 16-5c represents the biomechanical properties of the body segments of the USAF 50th percentile man. Table 16-5d gives regression equations for computing the mass of body segments from total body weight. These were determined from a reanalysis of the data in references (35) and (77). Calculations have also been made of the CG's and moments of inertia. Table 16-6a presents the centers of gravity and moments of inertia of the total body of 50th percentile USAF male population in different postures given in British Engineering Units; Figure 16-6b gives similar data in the metric system with regression equations. Table 16-6c represents formulas which can be used to calculate moments of inertia of body segments. In Table 16-6d, the moments of inertia of these segments are shown for two body positions. Tables 16-11 b, c, and d present the effect of pressure suits on centers of gravity and moments of inertia of subjects in pressure suits (346).

Inertial data of these types have been used to predict with reasonable accuracy dynamic responses of man in orbital weightlessness (197, 206, 358) and for impact dynamics (47). In preliminary tests, these models appear to offer much in terms of semiquantitative prediction of body response to work tasks under subgravity as well as under the zero gravity condition. Prime use is in analysis of work, self-rotation maneuvers, and translation potentials of men in zero gravity. The data have also been used in the design of control systems for astronaut maneuvering units (AMU) and other EVA devices (189, 322). Computer models of these systems (86, 206, 281, 297, 358, 372) appear to offer a better solution to these dynamic problems. Problems of hydrodynamic mass and drag areas during underwater simulation of weightlessness are covered in the discussion of Figures 7-68 and Table 7-69.

Figure 16-5

Centers of Gravity and Specific Gravity of Man



a. Diagram of Hinge Points and Centers of Mass

(After Whitsett (358))

Hinge Point and Symbol*	Coordinates (Inches)		
	X	Y	Z
Neck • A	0	0	59.08
Shoulder • B	0	7.88	56.50
Elbow • C	0	7.88	43.50
Hip • D	0	3.30	34.52
Knee • E	0	3.30	18.72
Mass Center and Symbol*			
Head ○ 1	0	0	64.10
Torso ○ 2	0	0	46.80
Upper Arm ○ 3	0	7.88	50.83
Lower Arm ○ 4	0	7.88	39.20
Hand ○ 5	0	7.88	31.68
Upper Leg ○ 6	0	3.30	27.68
Lower Leg ○ 7	0	3.30	11.80
Foot ○ 8	2.45	3.30	1.37

b. Coordinates of the Segment Hinge Points and Mass Centers
of USAF 50th Percentile Man

(After Whitsett (358))

Figure 16-5 (continued)

Segment	Weight (lbs)	Density (lbs/ft ³)	Length (inches)	Centroid Location (% length)
Head	11.20	71.6	10.04	50.0
Torso	78.90	68.6	24.56	50.0
Upper Arm	5.10	70.0	13.00	43.6
Lower Arm	3.03	70.0	10.00	43.0
Hand	1.16	71.7	3.69	50.0
Upper Leg	16.33	68.6	15.80	43.3
Lower Leg	8.05	68.6	15.99	43.3
Foot	2.39	68.6	2.73	50.0

c. Biomechanical Properties of the Segments of the USAF 50th Percentile Man

(After Whitsett⁽³⁵⁸⁾ from the data of Clauser, Hertzberg et al⁽¹⁶⁵⁾, and Dempster⁽⁷⁷⁾)

Body Segment	Regression Equation	Standard Deviation of the Residuals
Head, neck and trunk	= 0.47 x Total body wt. + 5.4	(± 2.9)
Total upper extremities	= 0.13 x Total body wt. - 1.4	(± 1.0)
Both Upper arms	= 0.08 x Total body wt. - 1.3	(± 0.5)
Forearms plus hands ^a	= 0.06 x Total body wt. - 0.6	(± 0.5)
Both forearms ^a	= 0.04 x Total body wt. - 0.2	(± 0.5)
Both hands	= 0.01 x Total body wt. + 0.3	(± 0.2)
Total lower extremities	= 0.31 x Total body wt. + 1.2	(± 2.2)
Both upper legs	= 0.18 x Total body wt. + 1.5	(± 1.6)
Both lower legs plus feet	= 0.13 x Total body wt. - 0.2	(± 0.9)
Both lower legs	= 0.11 x Total body wt. - 0.9	(± 0.7)
Both feet	= 0.02 x Total body wt. + 0.7	(± 0.3)

^a N = 11, all others N = 12.

d. Regression Equations for Computing the Mass (in kg) of Body Segments

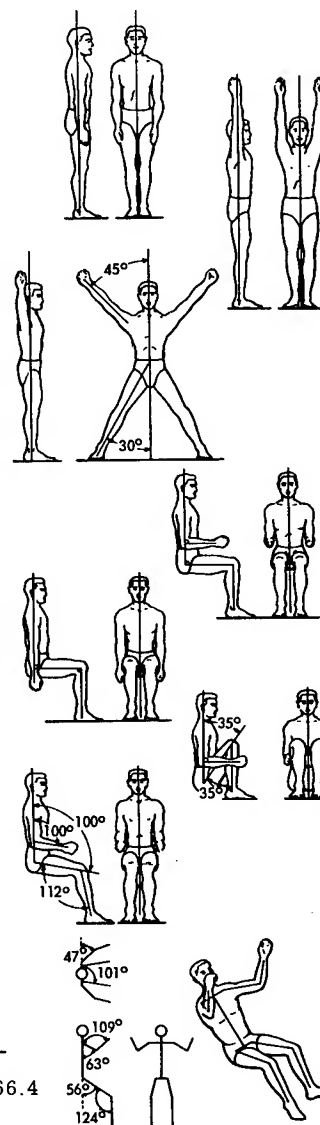
(From Barter⁽²²⁾)

Figure 16-6

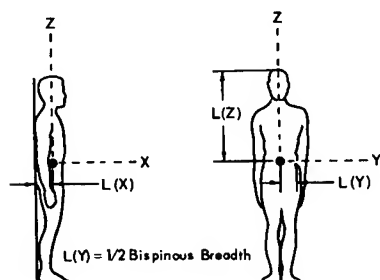
Centers of Gravity and Moments of Inertia of USAF Males in Different Postures

a. Whole-Body (British Engineering Units)

	Axis	Center of Gravity		Moment of Inertia	
		(in.)		(lb-in.-sec ²)	
		Mean	S. D.	Mean	S. D.
1. Standing	x	3.5	0.20	115.0	19.3
	y	4.8	0.39	103.0	17.9
	z	31.0	1.45	11.3	2.2
2. Standing, arms over head	x	3.5	0.22	152.0	26.1
	y	4.8	0.39	137.0	25.3
	z	28.6	1.33	11.1	1.9
3. Spread eagle	x	3.3	0.19	151.0	27.1
	y	4.8	0.39	114.0	21.3
	z	28.5	1.90	36.6	7.9
4. Sitting	x	7.9	0.36	61.1	10.3
	y	4.8	0.39	66.6	11.6
	z	26.5	1.14	33.5	5.8
5. Sitting, fore-arms down	x	7.7	0.34	62.4	9.7
	y	4.8	0.39	68.1	12.0
	z	26.8	1.16	33.8	5.9
6. Sitting, thighs elevated	x	7.2	0.37	39.1	6.0
	y	4.8	0.39	38.0	5.8
	z	23.1	0.78	26.3	5.1
7. Mercury configuration	x	7.9	0.34	65.8	10.3
	y	4.8	0.39	75.2	14.0
	z	27.1	1.14	34.2	5.6
8. Relaxed (Weightless)	x	7.3	0.33	92.2	13.3
	y	4.8	0.39	88.2	13.3
	z	27.5	1.44	35.9	5.4



Sample size 66. Mean age 33.2 yrs; S. D. age 7.2 yrs. Mean weight 166.4 lbs; S. D. weight 19.8 lbs. Mean stature 69.4 in; S. D. stature 2.9 in.



The location of the centers of gravity of the body was measured along the Z-axis from the top of the head, $L(Z)$, along the X-axis from the back plane, $L(X)$, and along the Y-axis from the anterior superior spine of the ilium, $L(Y)$. However, since body symmetry with respect to the sagittal plane was assumed, $L(Y)$ is defined as equal to one-half bispinous breadth (distance between anterior-superior iliac spines).

(After Hertzberg and Clauser⁽¹⁶⁴⁾, adapted from Santschi et al⁽²⁷⁹⁾)

Figure 16-6 (continued)

b. Whole-Body (Metric Units) - with Correlation Coefficients and Regression Equations Relating Stature and Weight to Moment of Inertia (N = 66)

Position	Axis	Center of Gravity ^a (Cm)		Moment of Inertia (Gm Cm ² x 10 ⁶)		R _{1,sw}	S.E.	Moment of Inertia Regression Equations ^b (Gm Cm ² x 10 ⁶)		
		Mean	S.D.	Mean	S.D.					
Standing (arms at sides)	X	8.9	0.51	130.0	21.8	.98	4.73	-262.0	+1.68S	+1.28W
	Y	12.2	0.99	116.0	20.6	.96	5.96	-240.0	+1.53S	+1.15W
	Z	78.8	3.68	12.8	2.5	.93	0.95	-0.683	-0.044S	+0.279W
Standing (arms over head)	X	8.9	0.56	172.0	29.5	.98	6.36	-371.0	+2.39S	+1.63W
	Y	12.2	0.99	155.0	28.6	.96	7.79	-376.0	+2.38S	+1.47W
	Z	72.7	3.38	12.6	2.1	.86	0.98	1.6	-0.038S	+0.234W
Spread Eagle	X	8.4	0.48	171.0	30.6	.98	5.54	-399.0	+2.51S	+1.69W
	Y	12.2	0.99	129.0	24.1	.96	7.06	-305.0	+1.91S	+1.29W
	Z	72.4	4.82	41.4	8.9	.93	3.19	-114.0	+0.677S	+0.484W
Sitting (elbows at 90°)	X	20.1	0.91	69.1	10.6	.92	4.53	-104.0	+0.637S	+0.804W
	Y	12.2	0.99	75.4	13.1	.92	5.10	-153.0	+1.01S	+0.669W
	Z	67.3	2.89	37.9	6.6	.97	1.64	-59.6	+0.34S	+0.502W
Sitting (forearms down)	X	19.6	0.86	70.5	11.0	.91	4.50	-89.0	+0.574S	+0.771W
	Y	12.2	0.99	77.0	13.6	.92	5.28	-144.0	+0.913S	+0.802W
	Z	68.1	2.95	38.2	6.7	.97	1.54	-60.8	+0.341S	+0.514W
Sitting (thighs elevated)	X	18.3	0.94	44.2	6.8	.89	3.16	-38.2	+0.242S	+0.529W
	Y	12.2	0.99	43.0	6.6	.77	4.14	-25.1	+0.193S	+0.449W
	Z	58.7	1.98	29.7	5.8	.92	2.26	-34.4	+0.146S	+0.509W
Mercury Position	X	20.1	0.86	74.4	10.6	.93	4.24	-107.0	+0.699S	+0.768W
	Y	12.2	0.99	85.1	15.8	.94	5.61	-198.0	+1.27S	+0.794W
	Z	68.8	2.89	38.7	6.3	.96	1.85	-50.9	+0.297S	+0.492W
Relaxed (weightless)	X	18.5	0.84	104.0	15.0	.96	4.20	-120.0	+0.788S	+1.13W
	Y	12.2	0.99	99.8	15.0	.94	5.13	-157.0	+1.08S	+0.879W
	Z	69.9	3.66	40.6	6.1	.96	1.74	-53.4	+0.346S	+0.440W

^a Location of CGs are with respect to the back plane, anterior superior spine of the ilium, and top of the head.

^b S is stature in centimeters; W is weight in kilograms.

(After Damon et al⁽⁷¹⁾, adapted from Santschi et al⁽²⁷⁹⁾)

c. Formulas for Calculating Local Moments of Inertia of Body Segments

Segment	Moments of Inertia		
	$I_{x_{cg}}$	$I_{y_{cg}}$	$I_{z_{cg}}$
Head	$\frac{1}{5} m(a^2 + b^2)$	$I_{x_{cg}}$	$\frac{2}{5} m a^2$
Torso	$\frac{1}{12} m(3a^2 + l^2)$	$\frac{1}{12} m(3b^2 + l^2)$	$\frac{1}{4} m(a^2 + b^2)$
Upper and Lower Arms and Legs	$m \left[A \left(\frac{m}{\delta l} \right) + B l^2 \right]$	$I_{x_{cg}}$	$2 \frac{m^2}{\delta l} A$
Hand	$\frac{2}{5} m \left(\frac{d}{2} \right)^2$	$I_{x_{cg}}$	$I_{x_{cg}}$
Foot	$\frac{1}{6} m l^2$	$\frac{1}{12} m(c^2 + l^2)$	$I_{y_{cg}}$

m = mass

l = length

a = semi-major axis

A and B are constants for segments (see Ref.358)

b = semi-minor axis

c = instep length of foot

d = diameter

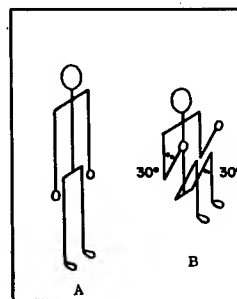
δ = average density

(After Whitsett⁽³⁵⁸⁾)

Figure 16-6 (continued)

d. Moments of Inertia of the Segments of 50th Percentile
USAF Man for Two Positions

		Segments*							
		Head	Torso	Upper Arms	Lower Arms	Hands	Upper Legs	Lower Legs	Feet
$I_{x_{cc}}$	Position A	0.0183	1.0000	0.0157	0.0056	0.0004	0.0776	0.0372	0.0006
	Position B	0.0183	1.0000	0.0157	0.0044	0.0004	0.0620	0.0372	0.0006
mD^2	Position A	1.5114	1.0125	0.2199	0.0405	0.0292	0.4964	1.3114	0.7388
	Position B	0.7859	0.0092	0.0932	0.0407	0.0303	0.1496	0.0588	0.1252
I_x	Position A	1.5297	2.0125	0.2356	0.0461	0.0296	0.5740	1.3486	0.7394
	Position B	0.8042	1.0092	0.1089	0.0451	0.0307	0.2116	0.0960	0.1258
$I_{y_{cc}}$	Position A	0.0183	0.9300	0.0157	0.0056	0.0004	0.0776	0.0372	0.0028
	Position B	0.0183	0.9300	0.0157	0.0056	0.0004	0.0776	0.0372	0.0028
mD^2	Position A	1.5114	1.0125	0.1517	0.0000	0.0137	0.4582	1.2925	0.7361
	Position B	0.7950	0.0734	0.0292	0.0002	0.0188	0.1190	0.1015	0.1560
I_y	Position A	1.5297	1.9425	0.1674	0.0056	0.0141	0.5358	1.3297	0.7389
	Position B	0.8133	1.0034	0.0449	0.0058	0.0192	0.1966	0.1387	0.1588
$I_{z_{cc}}$	Position A	0.0124	0.2300	0.0018	0.0008	0.0004	0.0154	0.0037	0.0028
	Position B	0.0124	0.2300	0.0018	0.0020	0.0004	0.0310	0.0037	0.0028
mD^2	Position A	0.0000	0.0001	0.0682	0.0405	0.0155	0.0382	0.0188	0.0085
	Position B	0.0091	0.0642	0.0723	0.0405	0.0195	0.0459	0.0804	0.0420
I_z	Position A	0.0124	0.2301	0.0700	0.0413	0.0159	0.0536	0.0226	0.0113
	Position B	0.0215	0.2942	0.0742	0.0426	0.0199	0.0763	0.0841	0.0448



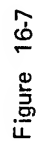
*Positions A and B are shown in figure.

†All values are slug-ft².

Determination of specific gravity can be made from anthropometric data (70). Attempts have been made to relate the specific gravity of different individuals to the somato type classification of Sheldon (85, 250). This formula for specific gravity works only for navy divers for which it was developed. It failed to predict densitometrically determined density (or specific gravity) or percentage of body fat among athletic young men (70). The best prediction of density is actually based on averaging two skin fold measurements by the equations (253): Density = $1.0923 - 0.0203$ (triceps skinfold, in cm.); Density = $1.0896 - 0.0179$ (subscapular skinfold, in cm.). To obtain fat from density, Fat = $(4.0439/\text{density} - 3.6266)$. This formula of Grande is based on a reference man with 17.8% of total body fat (121).

The dimensions of a typical 5th to 95th percentile, seated, pilot operator are seen in Figure 16-7. Data are available on three-dimensional arm reach in the seated position (71, 192). Data are also available on the design of new seat concepts for aerospace vehicles (258) (see also sections on Impact No. 7, and Vibration No. 8. Figure 16-8 covers workspace requirements for the 95th percentile USAF population.

Body areas are needed for thermal and energetic analyses. (See Thermal Environment, (No. 6) and Oxygen-CO₂-Energy, (No. 10). Table 6-22 represents a cylindrical model of man for calculation of heat transfer coefficients. Figure 6-16 is a nomograph for calculation of the surface area of the USAF male population from height and weight data. Figure 10-13 is a graph which can be used in the same calculation for the average male population. In analysis of radiative heat transfer, the total radiation area (Figure 6-17) and the projected areas (Figure 6-18) can be used (133, 164, 291). Drag areas and hydrodynamic mass of suited subjects are presented in Figure 7-68 and



Dimensions of the Seated Operator

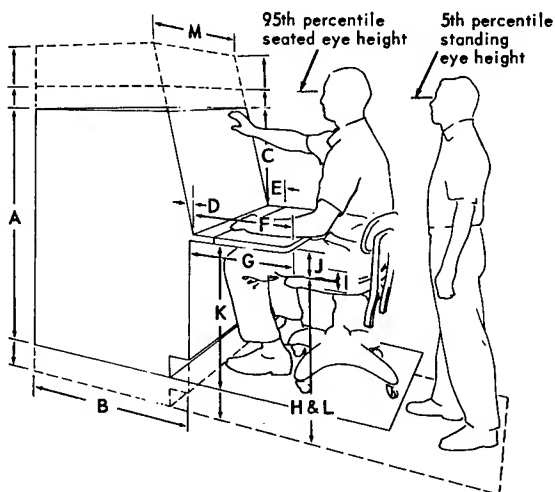
(After Hertzberg and Clauser⁽¹⁶⁴⁾.)

Dimensions (in inches) of nude seated pilots, 5th to 95th percentile. Normal flight position is shown at left, ejection position on the right. SRP is the seat reference point, from which the horizontal (H) plane is defined for and aft (x co-ordinates) and side to side (y co-ordinates). L means "line," as in VSRL - vertical seat reference line, in the Z direction.

Source: Chaffee (55)

Table 16-8

Work Space Dimensions

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Type of Console	Maximum console height from standing surface	Console depth at base	Vertical dimension of panel, including sills	Console panel angle-- from vertical	Minimum pencil-shelf depth	Minimum writing surface depth-- including pencil shelf	Minimum knee clearance	Foot support to seat ¹	Seat adjustability	Minimum thigh clearance at midpoint of "I"	Writing surface height from standing surface	Seat height at midpoint of "I"	Maximum console panel breadth
	A	B	C	D	E	F	G	H	I	J	K	L	M
1. Sit-Stand	62.0	Opt.	26	15°	4	16	18	18	4	6.5	36.0	28.5	36
2. Sit (w/vision over top)	47.5* to 58.0	Opt.	22	15°	4	16	18	18	4	6.5	25.5 to 36.0	18.0 to 28.5	36
3. Sit (w/o vision over top)	51.5** to 62.0	Opt.	26	15°	4	16	18	18	4	6.5	25.5 to 36.0	18.0 to 28.5	36
4. Stand (w/vision over top)	62.0	Opt.	26	15°	4	18	--	--	--	--	36.0	---	36
5. Stand (w/o vision over top)	72.0	Opt.	36	15°	4	16	--	--	--	--	36.0	---	36

* "A" must never be more than 29.5 inches greater than "L".
 ** "A" must never be more than 33.5 inches greater than "L".

¹ When seat-to-standing surface exceeds 18", a heel catch should be provided.

Table of standard values for critical dimensions used in the design of instrument consoles for the seated and/or standing operator, with and without a requirement on the operator to maintain horizontal visual contact with other displays or test apparatus beyond the console. Design values for each console established to accommodate 95+ percent of USAF population.

Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

Table 7-69. Buttock contact areas and thigh dimensions for the specific population indicated are seen in Figure 16-9.

Presence of clothing increases the body dimensions. Group support equipment in space operations often makes use of military support. Figure 16-10 covers the increase dimensions to be expected from clothing on support personnel.

The increase in body dimensions resulting from pressure-suit wear will vary with design of the suit. Table 16-11a covers increases from the USAF MC-2 suits. Tables 16-11b and c present changes in body dimensions of astronauts in NASA soft and hard suits. Figure 16-11d shows the changes in center of gravity; and Tables 16d and e, the changes in center of gravity and moment of inertia of the whole body produced by space suits, pressurized and unpressurized. Table 16-11f gives regression equations which can be used to calculate these changes in moments of inertia from data on body weight.

Stowage volumes for soft (223) and hard (26) suits have been determined. The soft suit may be packed into a slab volume 64 x 27 x 7 inches and the slab arched along its length with a radius of 49 inches. The helmet can be considered a sphere of about 16 inches maximum diameter; and back pack, a volume of about 12x16x9 inches. The hard suit can be stowed in a volume of 46x25x16 inches including helmet. These dimensions are only approximate values for typical prototype suits.

Workspace Factors

Division of workspace into functional compartments must also be considered (54, 93, 109, 266). (See also section on Confinement).

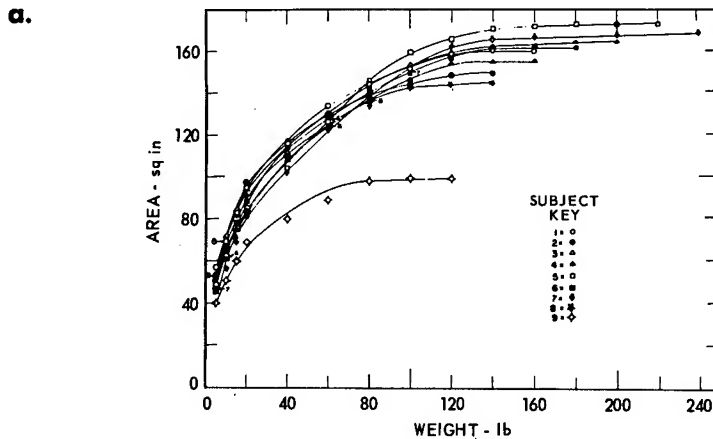
In the Mercury spacecraft there was an internal volume of approximately 54 cubic feet of which 4 cubic feet was occupied by the astronaut. Since the astronaut was never required to leave his couch for either personal or mission requirements, such a limited volume could be tolerated over the period of even the longest mission of 22 orbits. The Gemini spacecraft, on the other hand, provided an internal volume of approximately 88 cubic feet or 11 cubic feet less per man than that provided by Mercury. Details of Gemini cabins are available (217, 231). Since the Gemini missions were considerably more demanding due to duration and extravehicular activities, the lack of significant, useable work space was exhibited by the constraints placed upon work/rest cycles, stowage provisions in and around the hatches, headrest areas, and limited leg movement in the foot-well, to name a few.

Although the Apollo command module spacecraft provides an internal volume of approximately 320 cubic feet, it must be remembered that this space is distributed across three couch stations, two work stations in the lower equipment bay, a guidance and navigation station, and two sleep stations under the couches. The cubage at these stations, though marginal, is sufficient to meet mission requirements provided that the intravehicular activity at the various stations is properly sequenced (244). However, for missions of longer duration, considerably greater volume at each station would have to be provided to meet increased stowage requirements. Based on these and similar considerations, (see section below on Confinement), the following

Figure 16-9

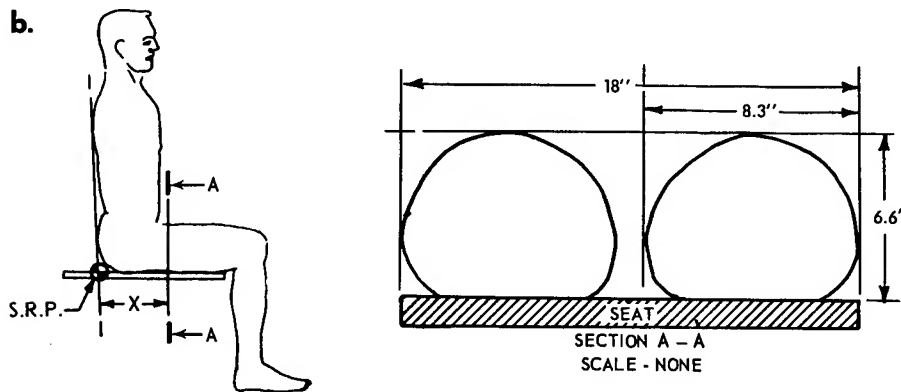
Buttock Areas and Thigh Dimensions

(After Hertzberg and Clauser⁽¹⁶⁴⁾)



Buttock contact areas of nine men who were gradually lowered onto a measuring plate until their full weights were supported. Subjects fell within the following ranges: age 27-41 years; height 66-74 inches; weight 120-269 pounds. When these contact areas had been established, loads were increased by having the subjects hold weights in their arms to determine what increase in contact area would result. Loads of 20, 40, and 60 pounds caused no measurable increase in buttock contact area.

(Adapted from Swearingen et al⁽³¹⁹⁾)



Height and width of the thighs, shown on the right, from a section taken just ahead of the intersection of thigh and trunk as shown in the drawing on the left. The x distance from the Seat Reference Point (SRP) to the section varied from 9.5 to 12 inches. Dimensions for the thigh are 95th percentiles, meaning that 5% of the AF flying population will have larger dimensions. The thigh heights were measured, the thigh widths computed from the relation: Width = 1.37 Height.

(Adapted from Esch⁽⁹¹⁾)

Table 16-10

Increase in Dimensions from Clothing

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

	Civilians		Army				Air Force		
	Men street clothing	Women street clothing	summer uniform	fall uniform	winter uniform	winter combat	full flight gear	light flight assembly	winter flight assembly
weight (lbs)	5.0	3.5	9.4	11.8	18.6	22.9			20.0
stature	1.0	0.5-3.0	2.65	2.65	2.65	2.75	-2.0	3.3	1.9
abdomen depth			0.94	1.18	1.95	2.54	5.0		1.4
arm reach, anterior			0.04	0.08	0.20	0.37			0.4
buttock-knee length			0.20	0.30	0.54	0.70	2.0		0.5
chest breadth							2.5		0.6
chest depth			0.41	0.96	1.80	1.54	4.5	0.8	1.4
elbow breadth			0.56	1.04	1.84	2.12	11.0		4.4
eye level height, sitting			0.04	0.08	0.16	0.22			0.4
foot breadth	0.3		0.20	0.20	0.20	0.20			1.2
foot length	1.2		1.60	1.60	1.60	1.60			2.7
hand breadth						0.30			0.4
hand length						0.15			0.3
head breadth			2.8	2.8	2.8	2.8			0.4
head length			3.5	3.5	3.5	3.5			0.4
head height			1.35	1.35	1.35	1.45			0.2
hip breadth			0.56	0.76	1.08	1.40			1.3
hip breadth, sitting			0.56	0.76	1.08	1.40	5.5	2.9	1.7
knee breadth			0.48	0.48	0.72	1.68	9.5		2.5
knee height, sitting			1.32	1.32	1.44	1.44			1.8
shoulder breadth			0.24	0.88	1.52	1.16	6.0	0.4	1.3
shoulder-elbow length			0.14	0.50	0.94	0.62			0.3
shoulder height, sitting			0.16	0.58	0.92	0.80			0.6
sitting height			1.39	1.43	1.61	1.67		2.1	0.6

(All dimensions are given in inches)

Civilians, men: underwear, shirt, trousers, tie, socks, shoes.

Civilians, women: underwear, dress, or blouse or sweater and skirt, shoes.

Army, summer uniform: underwear, khakis or O. D. 's or fatigues, socks, shoes, helmet and liner

Army, fall uniform: underwear, khakis or O. D. 's or fatigues, blouse or field jacket, socks, shoes, helmet and liner.

Army, winter uniform: underwear, khakis or O. D. 's or fatigues, blouse or field jacket, overcoat, socks, shoes, helmet and liner.

Army, winter combat: underwear, khakis or O. D. 's or fatigues, combat suit, overcoat, socks, shoes, gloves, wool cap, helmet and liner.

Air Force, full flight gear: T-1 partial pressure suit, inflated, ventilation suit, deflated, MD-1 anti-exposure suit and MD 3A liner, long cotton underwear.

Air Force, light flight assembly: T-5 partial pressure suit, uninflated, K-1 pressure helmet and boots

Air Force, winter flight assembly: World War II heavy winter flying clothing, including jacket, trousers, helmet, boots, and gloves.

Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

Figure 16-11

Anthropometric Study of Pressure Suits

a. Increase in Dimensions from Soft, Full Pressure Suits

Measurement	Nude		Uninflated		Inflated	
	Median	Range	Median	Range	Median	Range
shoulder circumference	48.3	(45.1-50.5)	56.1	(54.7-61.0)	63.0	(60.0-65.0)
chest circumference	39.6	(37.7-42.2)	48.3	(48.0-52.0)	52.5	(50.5-54.2)
waist circumference	34.3	(32.0-38.8)	44.4	(42.0-47.2)	47.3	(45.2-50.0)
upper thigh circumference	25.1	(22.3-26.0)	25.7	(24.5-28.0)	27.0	(25.3-29.0)
lower thigh circumference	17.0	(15.6-18.5)	20.8	(18.2-23.6)	22.1	(21.1-24.5)
calf circumference	14.9	(14.5-17.0)	16.9	(16.2-19.4)	18.3	(16.9-19.9)
ankle circumference	9.2	(8.9-10.5)	12.1	(11.4-13.6)	12.1	(12.0-13.8)
biceps circumference	13.5	(12.7-14.5)	14.8	(14.0-16.3)	16.2	(14.9-17.0)
wrist circumference	7.0	(6.6- 7.2)	8.1	(7.9- 8.4)	9.0	(8.3- 9.2)
vertical trunk circumference	67.4	(64.4-71.5)	66.8	(64.9-70.0)		
knee circumference	15.9	(15.0-17.1)	22.1	(20.0-23.0)	21.8	(20.0-23.4)
vertical trunk circumference	64.2	(63.7-67.5)	66.5	(65.0-69.6)	67.3	(66.0-70.4)
buttock circumference	42.0	(39.1-45.5)	46.7	(45.3-51.0)	49.9	(47.3-51.0)
shoulder breadth	19.2	(18.2-19.8)	20.6	(18.6-22.0)	23.7	(13.8-25.5)
chest breadth	13.0	(10.9-12.9)	13.8	(12.7-15.1)	14.7	(14.4-15.6)
hip breadth	13.7	(12.9-14.4)	15.4	(14.1-16.3)	17.4	(16.2-18.6)
hip depth	10.3	(9.5-12.0)	11.4	(10.8-11.7)	15.0	(15.0)
chest depth	10.2	(9.8-10.7)	13.1	(12.1-13.5)	14.9	(14.2-15.2)
elbow-elbow breadth	19.9	(18.6-22.1)	23.2	(20.7-25.1)	27.7	(25.8-30.1)
knee-knee breadth	8.2	(7.8- 9.3)	12.0	(10.7-13.5)	21.3	(18.6-22.6)
sitting height	35.7	(34.7-37.7)	34.8	(33.7-36.2)	36.8	(35.6-38.5)
eye height	31.2	(29.6-33.0)	30.4	(28.4-31.7)	31.3	(29.4-32.2)
shoulder height	23.5	(22.7-24.9)	23.5	(22.1-24.5)	24.3	(23.4-25.3)
knee height	21.9	(21.3-22.8)	23.3	(22.6-23.9)	24.0	(22.9-24.6)
popliteal height	17.5	(17.2-19.8)	18.1	(17.0-18.4)	18.2	(16.8-18.9)
elbow rest height	7.8	(7.5- 9.1)	8.2	(6.3-10.1)	10.0	(9.5-11.0)
shoulder-elbow length	15.0	(14.2-15.4)	15.4	(14.5-16.1)	15.8	(15.2-16.0)
forearm-hand length	19.2	(18.5-20.0)	19.4	(18.9-20.3)	19.8	(18.6-20.7)
foot length	10.5	(10.3-11.0)	12.6	(11.8-12.7)	12.3	(11.7-12.6)
hand length	7.7	(7.5- 8.5)	7.5	(7.2- 7.7)	7.1	(6.8- 7.5)
palm length	4.5	(4.4- 4.5)	3.5	(3.9- 4.3)	4.0	(3.2- 5.9)
crotch height (standing)	33.3	(31.1-34.8)	32.4	(30.8-33.4)		
thigh clearance	6.5	(5.5- 7.1)	6.4	(6.1- 7.0)	8.1	(7.6- 8.2)

All measurements were taken on seated subject, except crotch height. All dimensions are given in inches. These measurements were taken on six subjects wearing the MC-2(X-15 type) full-pressure suit.

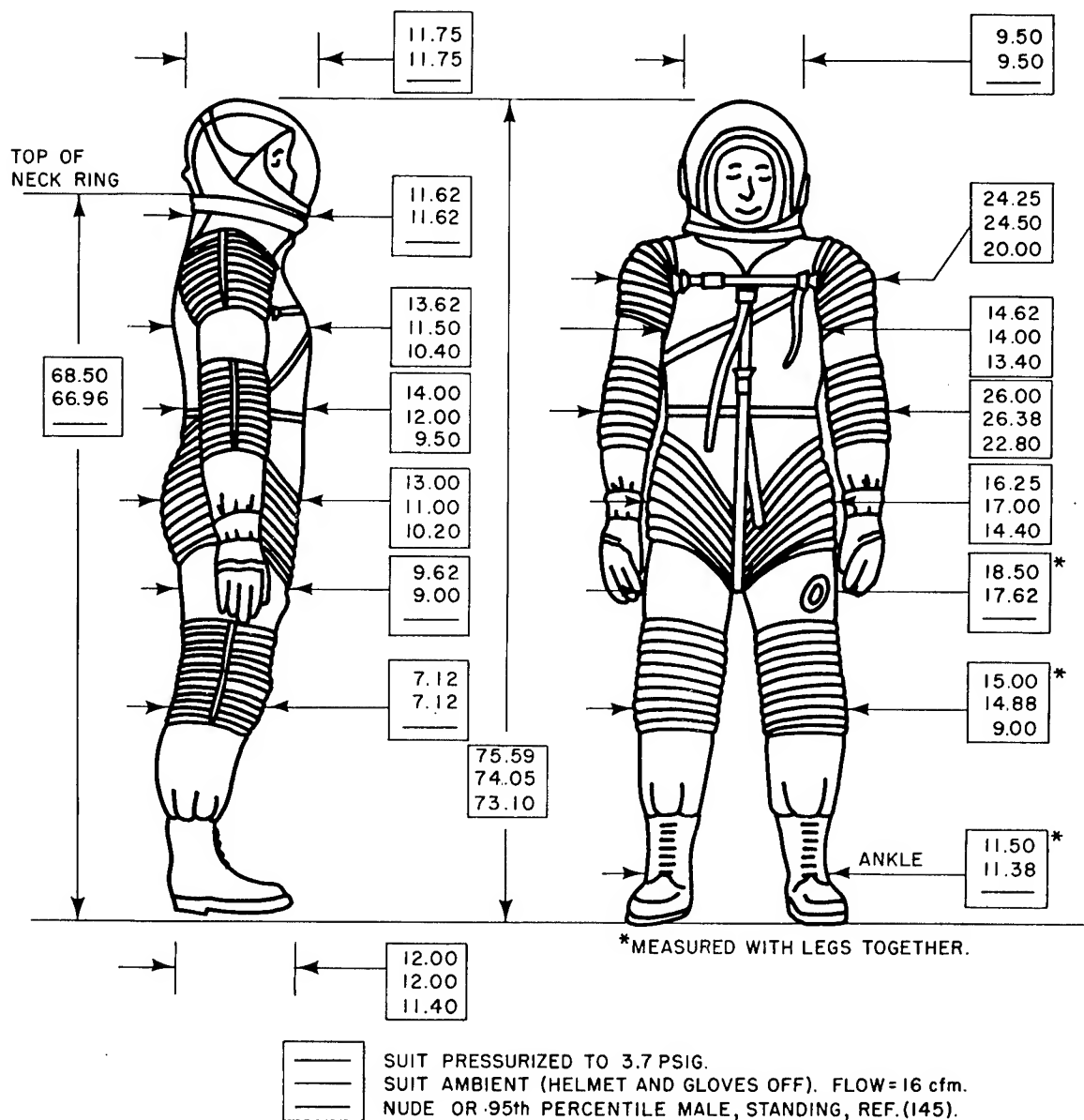
Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Figure 16-11 (continued)

b. Maximum Dimensions of a NASA Prototype, Soft, Full-Pressure Suit in the Unpressurized and Pressurized Condition

These data, noted in indices, cover the large-long size of a S/N007 or (A6L) PGA designed for a subject 6', 1.5" tall and 190 lbs weight, representing approximately the 95th percentile male. Extra vehicular operations require an addition to the total height of 1.5" for the EVVA visor assembly and 0.6" for EV boots giving a total standing height, pressurized, of 77.71 inches.



ALL DIMENSIONS IN INCHES.

(After Feddersen and Reed⁽⁹⁴⁾)

Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit

The hard suit is composed of 6 body elements, each with up to 6 different sizes noted by Roman numerals. The suit described below is a composite of different body elements assembled for a specific astronaut. Adjustments for other sizes are noted after each specific element. All dimensions are noted in inches.

ELEMENT SIZES OF SUIT MEASURED	DIMENSION ADJUSTMENTS FOR OTHER SIZES
1. UPPER TORSO - SIZE III	SHOULDER BREADTH SIZE IV +1.00 SIZE I & II NO CHANGE
2. LOWER TORSO - SIZE III (Adjusted to the Short Position) (+.75" Adjustment possible)	LENGTH ONLY SIZE I -1.20 (Short Adjustment) II - .60 (Short Adjustment) IV +1.35 (Long Adjustment) V +1.95 (Long Adjustment) VI +2.55 (Long Adjustment)
3. UPPER ARM - SIZE IV	LENGTH CHANGE ONLY SIZE V + .40 I -1.20 II - .80 III - .40
4. FOREARM - SIZE III	LENGTH CHANGE ONLY SIZE I -1.40 II - .70 IV + .70
5. THIGH - SIZE II (Adjusted to Short Position) (+.87" Adjustment possible)	LENGTH CHANGE ONLY SIZE I - .70 (Short Adjustment) III +1.56 (Long Adjustment) IV +2.26 (Long Adjustment) V +2.96 (Long Adjustment)
6. CALF - SIZE II	LENGTH CHANGE ONLY SIZE I - .70 III + .60 IV +1.20 V +1.80 VI +2.40

(After Breslin, C. and Brosseau, P.L., Litton Systems, Inc.; Applied Technology Division, unpublished data, 1968)

Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

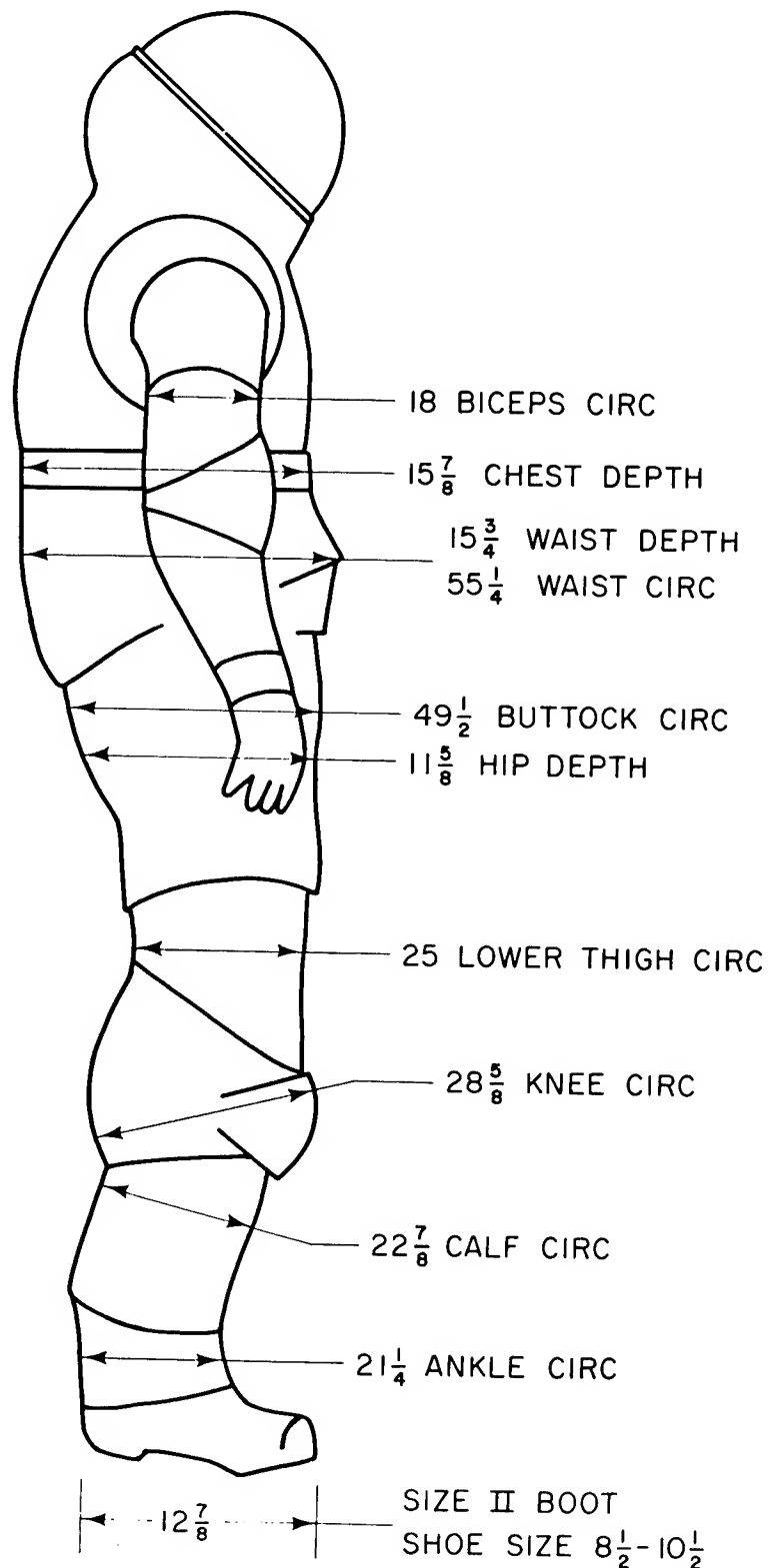


Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

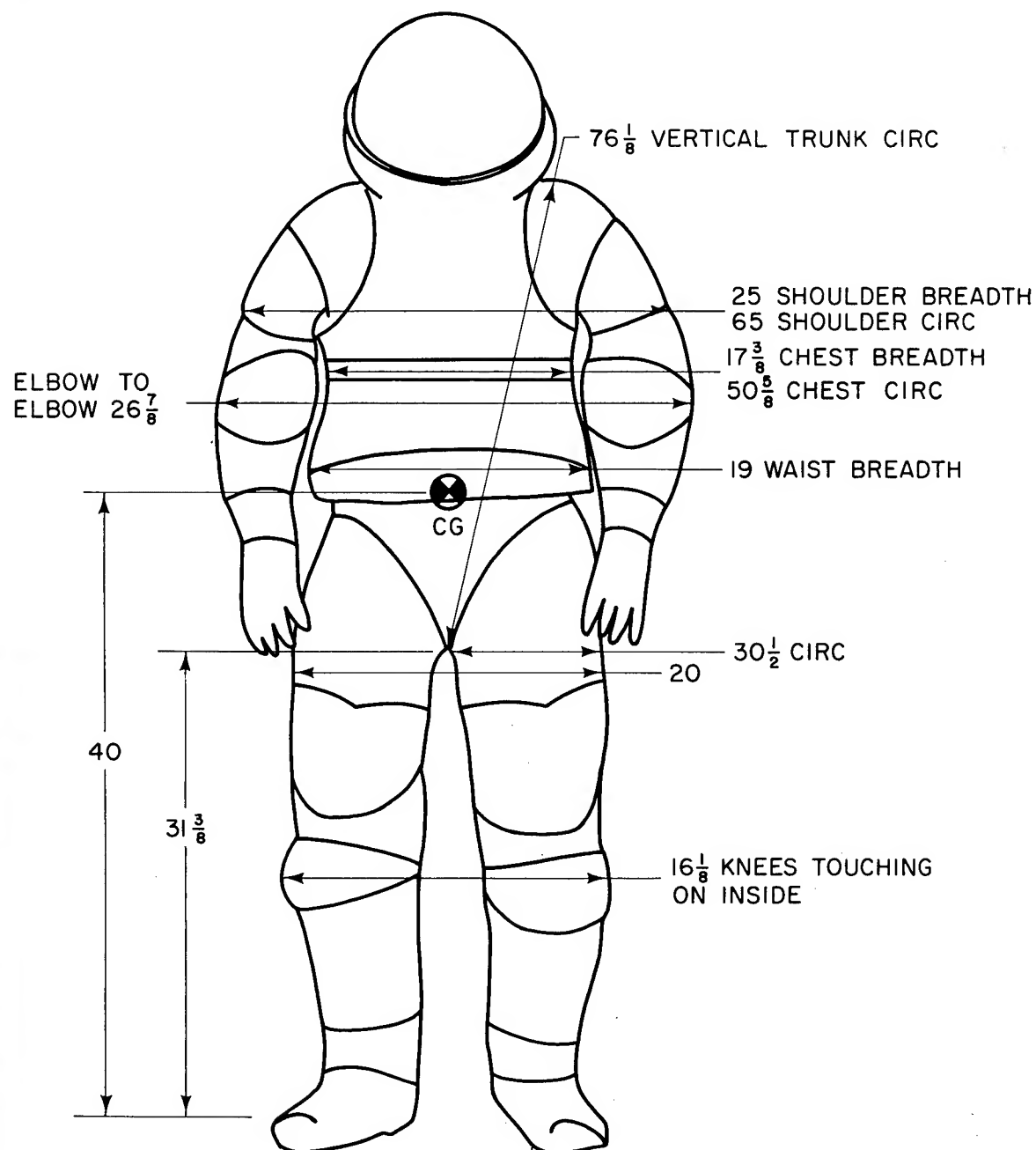


Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

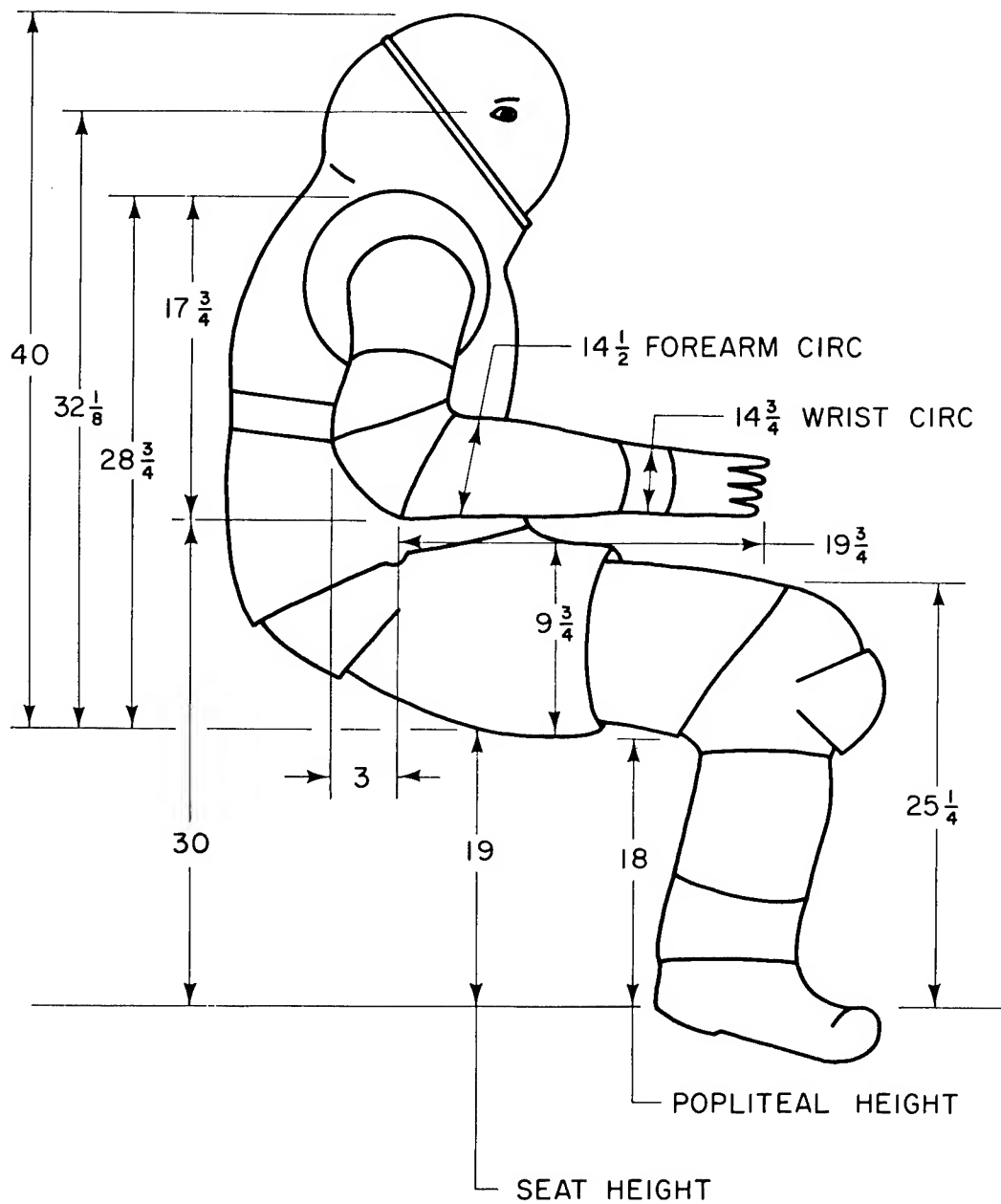
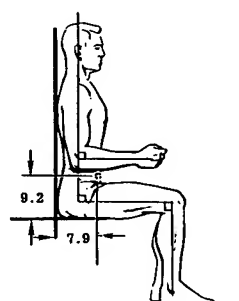
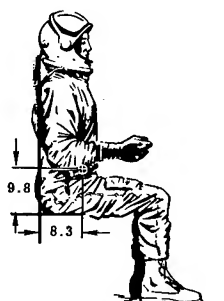


Figure 16-11 (continued)

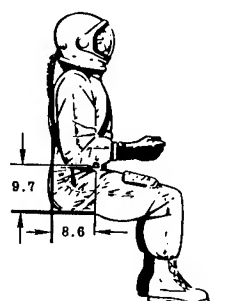
d. Mean Centers of Gravity of Pressure-Suited Subjects



Nude

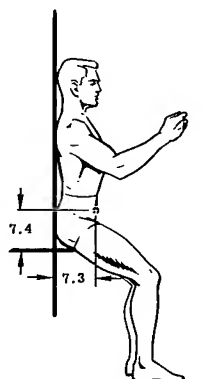


Unpressurized

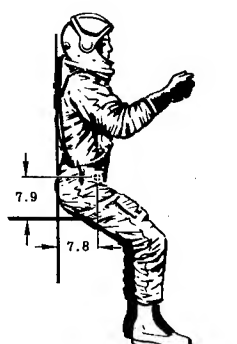


Pressurized

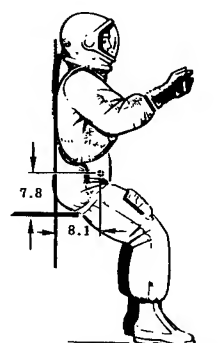
1. Sitting



Nude



Unpressurized



Pressurized

2. Relaxed (Weightless)

(After DuBois et al⁽⁸³⁾)

Figure 16-11 (continued)

e. Arithmetic Means and Standard Deviations of the Sample Centers of Gravity and Moments of Inertia (N = 19)

	Axis	Center of Gravity (in.)		Moment of Inertia (lb. in.sec. ²)	
		Mean	S.D.	Mean	S.D.
1. Sitting					
Nude	x	7.89	0.41	56.3	8.22
	y	4.79	0.27	66.5	9.98
	z	9.16	0.29	28.3	5.10
Unpressurized	x	8.33	0.39	67.5	9.16
	y	4.79	0.27	82.8	11.30
	z	9.76	0.30	33.6	5.72
Pressurized	x	8.62	0.38	68.8	8.70
	y	4.79	0.27	82.4	11.30
	z	9.70	0.28	34.0	5.72
2. Relaxed (Weightless)					
Nude	x	7.34	0.38	99.2	14.20
	y	4.79	0.27	89.8	15.20
	z	7.39	0.42	31.2	5.04
Unpressurized	x	7.81	0.30	118.0	15.30
	y	4.79	0.27	114.0	15.00
	z	7.86	0.45	36.2	5.03
Pressurized	x	8.08	0.29	118.0	15.20
	y	4.79	0.27	114.0	15.70
	z	7.81	0.48	36.1	4.85

Mean Age 27.4 yrs. S.D. Age 5.3 yrs.

Mean Weight 164.6 lbs. S.D. Weight 17.4 lbs.

Mean Stature 69.0 in. S.D. Stature 2.3 in.

Mean Clothing Weight 23.2 lbs. S.D. Clothing Weight 0.5 lb.

(After DuBois et al⁽⁸³⁾)

Figure 16-11 (continued)

f. Correlation of Moment of Inertia with Stature and Weight
in Pressure-Suited Subjects (N = 19)

	Axis	$R_{I,SW}$	S.E.*	I_0	Regression Equation*
1. Sitting					
Nude	x	0.95	2.67	-105.0	+ 1.59S + 0.317W
	y	0.91	4.07	-135.0	+ 2.10S + 0.344W
	z	0.97	1.17	- 70.4	+ 0.923S + 0.212W
Unpressurized	x	0.93	3.42	-114.0	+ 1.82S + 0.337W
	y	0.97	2.77	-181.0	+ 2.96S + 0.362W
	z	0.97	1.47	- 79.5	+ 1.09S + 0.229W
Pressurized	x	0.93	3.24	-120.0	+ 2.06S + 0.281W
	y	0.94	3.79	-157.0	+ 2.54S + 0.389W
	z	0.96	1.53	- 78.1	+ 1.07S + 0.230W
2. Relaxed (Weightless)					
Nude	x	0.97	3.30	-171.0	+ 2.88S + 0.556W
	y	0.95	4.60	-265.0	+ 4.04S + 0.461W
	z	0.94	1.75	- 46.0	+ 0.567S + 0.231W
Unpressurized	x	0.95	4.62	-197.0	+ 3.19S + 0.574W
	y	0.96	4.38	-217.0	+ 3.59S + 0.506W
	z	0.96	1.33	- 54.8	+ 0.801S + 0.217W
Pressurized	x	0.97	3.93	-208.0	+ 3.42S + 0.550W
	y	0.96	4.44	-254.0	+ 4.18S + 0.482W
	z	0.96	1.36	- 48.7	+ 0.720S + 0.214W

$$r_{sw} = 0.44 \quad S.E. = 2.02 \text{ in.} \quad S = 59.58 + 0.057W$$

* I_0 and S.E. in lb.in.sec.²

S in in.

W in lbs.

(After DuBois et al⁽⁸³⁾)

recommendations regarding minimal volumetric requirements for missions extending from a few months to a year may be made:

Sleep/rest station volume should not be less than 300 cubic feet per man and so configured as to accommodate stowage of spare clothing (constant-wear garments and flight coveralls), suit-inflation capability, and donning of the pressure suits.

Work station volume should be dictated by operational requirements and so designed as to meet the following criteria:

- Separate from sleep/rest station.
- Contingency functions designed for pressure suited interface and given priority consideration in location/placement.
- Individual pressurization capability.
- Unrestricted access to all controls and displays.
- Restraints and tethers to permit performance of all work functions with two hands if the need should arise.
- Non-interference between duty station crewmen if more than one is working.

Air locks and hatches should be designed so that the actuating mechanism is no higher than shoulder height and positioned for easy visual access in a standing, 1G position. For umbilical operations, the hatches should not be less than 31 inches in diameter and for operations with a self-contained life support system they should not be less than 43 inches in diameter to provide easy egress/ingress capability. Air locks should be designed to an inner diameter of at least 5 feet to provide pressurized turn-around capability and should contain a handrail or protruding handrails along the axis of body rotation. The air locks themselves should be designed for operation by one man with simple unlocking/locking mechanisms, with mechanical advantages for aid in overcoming residual pressure forces inside the spacecraft, and hinged for rotation to provide unencumbered access to tunnel areas.

Studies have been performed on the design of air locks and hatches in zero gravity operations. The subjects were filmed during repetitive trials and the position-velocity time profiles of the maneuvers were analyzed for three simulation modes; ground-normal gravity, aircraft-zero gravity, and water immersion neutral buoyancy. These simulation studies indicate that:

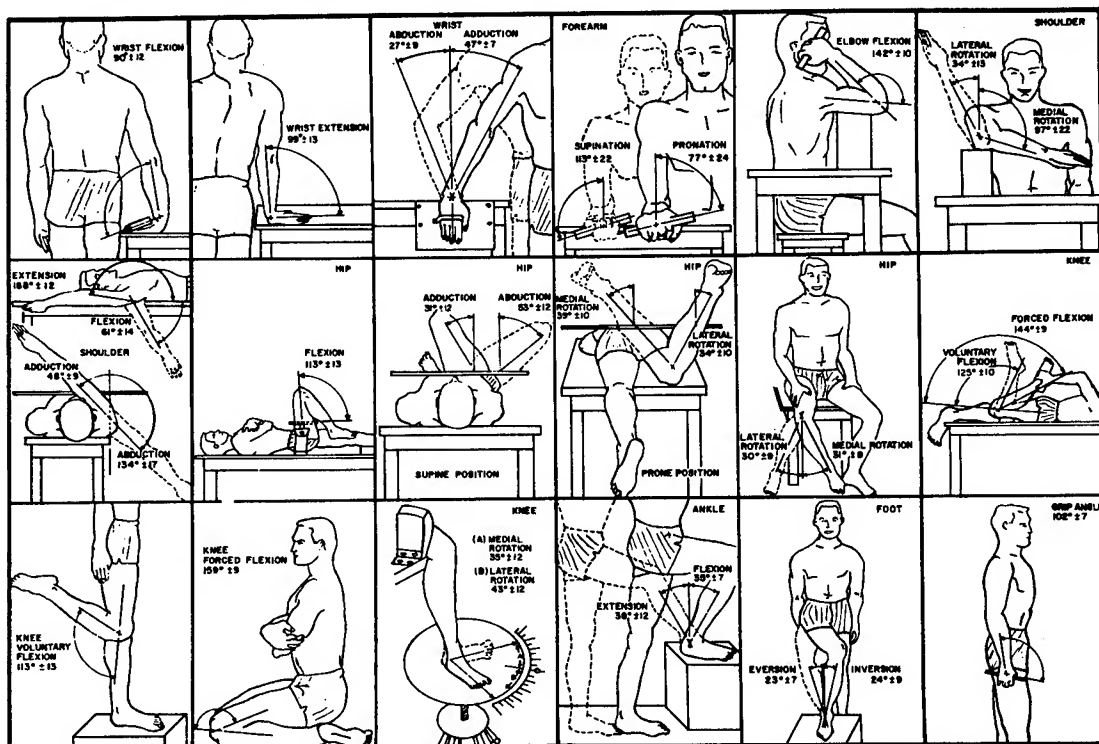
- A 48"-diameter, 6' length airlock passageway with 32" circular hatches is sufficient, from a space standpoint, for an astronaut to adequately perform a manual ingress-egress maneuver.
- Counter rotation to applied torques, and movement due to applied linear forces due to lack of gravity-dependent reaction forces of the body must be counteracted to insure adequate operation.
- Hatch diameters less than 26" should not be utilized due to impediment to free travel and suit interactions.

- Ingress-egress maneuvers in airlocks of 48" diameter or less, requiring internal turnaround of a pressure-suited astronaut, dictate strengthening of the suit faceplate to prevent accidental depressurization.
- Airlock hardware requiring operation by an astronaut in a pressurized suit must be sized to accommodate the lack of tactual and visual ability concomitant with pressure-suited operations.
- Airlock passageways should remain as free of hardware appurtenances as design factors dictate to prevent suit interaction.

Future space vehicles and lunar bases have been studied from the point of view of workspace. Optimization of laboratories and crew stations for large orbiting crafts (259) and other space vehicles (223) has received preliminary study. Workspace analysis has been performed for lunar laboratories and bases (49, 237).

Force-Motion Analysis

The range of body motion is an important factor in workspace and operations analysis. Figure 16-12 shows the joint motion capability of a young male population. The recorded motion range in the nude should not be much different for



Range of joint motion in 39 young men, showing the median value in degrees, ± 1 standard deviation. If ± 2 SD are taken, 95% of the sample of 39 is included. Compared with the 1950 Air Force survey of over 4000 flying men, this sample is 6.8 years younger, 6.0 lbs heavier, and 1.4 inches taller.

Figure 16-12

Joint Motion Capability of a Young Male Population

(After Hertzber and Clauser⁽¹⁶⁴⁾)

the typical astronaut in shirtsleeve environment. Dynamic characteristics and range of motions required for operation of lunar scientific equipment are given in References (115, 184) and in Tables 16-19 to 16-23.

Forces and angular motion exerted on sidearm controllers are noted in Figures 16-13a and b. Forces exerted on hand controls by male college students are noted in Figure 16-14a. Design of control devices can be quite complex. In the Gemini program, rudder pedals were initially envisaged; however, weight and space limitations forced abandonment of pedals in favor of placing a third axis on the manual controller (217). Either crew member could operate the controller while in the restrained position through wrist articulation and palm pivot motion only, to preclude body movements from being transmitted to the controller. The handle was spring loaded to provide an increasing resistance as the handle was moved away from neutral. Controller force/displacement originally had a step function designed in all three axes, but was later revised to a smooth curve as shown in Figure 6-14b for all three axes. Redundant switches were incorporated for selectivity energizing solenoid valves in the attitude control system. Total travel of the hand controller was 10 ± 1 degrees from neutral in pitch and yaw axes and 9 ± 1 degrees in the roll axis. Rotary movement of the handle about a transverse axis located at the palm pivot point effected a corresponding spacecraft motion about the pitch axis. Rotary displacement in a clockwise or counterclockwise direction in a transverse plane with respect to an adjustable canted axis below the pilot's wrist effected a similar movement about the spacecraft roll axis. Clockwise or counterclockwise rotation of the controller about the longitudinal axis of the handle effected a corresponding movement about the yaw axis. Due to extended operation in this mode, the resistant stick forces tended to cause wrist fatigue. Thus, the control stick was modified to assimilate a T at the top. This enabled the pilot to grasp the top of the stick palm down if desired for more ease of yaw control. A guard was built up on the top to prevent depressing the communications transmit buttons while grasping the stick in this manner. Evaluation of the many attitude controller designs included operation of the stick with a bare hand, a soft glove or a pressurized glove, as well as consideration of the man pressurized or unpressurized, in zero-g or under heavy re-entry g loads. The attitude controller worked best in conjunction with a rotary mode selector slightly forward and left of the stick. This was needed to allow the pilot minimal three-axis response for fine maneuvering such as docking (pulse) or larger orders of magnitude in response for gross corrections (rate command or direct). The modes made available to the pilot were:

a. HOR SCAN - The horizon sensors provided a reference in pitch and roll to automatically control a limit-cycle mode ± 5 degrees in these axes. The yaw axis was maintained by the pilot using the pulse mode which was maintained on all axes in this mode.

b. RATE CMD - Pitch, roll and yaw rate gyro outputs were compared with controller positions to produce attitude rates proportional to controller deflection. (Operationally, this mode was effective in correcting the fairly high cross coupling rates developed when the maneuver controller was used to translate.)

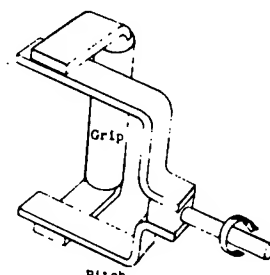
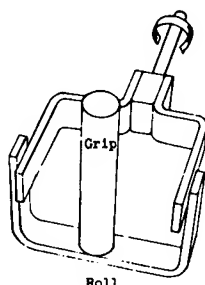
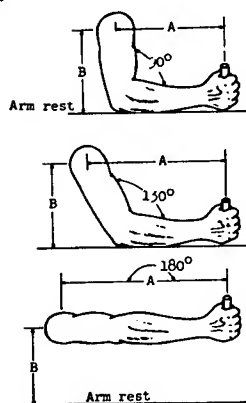
c. DIRECT - Provided direct control to open thrust chamber solenoids when the attitude controller was deflected approximately 25% of full travel. (The utmost discretion was used in this mode, as it tended to waste fuel.)

Figure 16-13

Forces Exerted on Side-Arm Controllers

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

a.

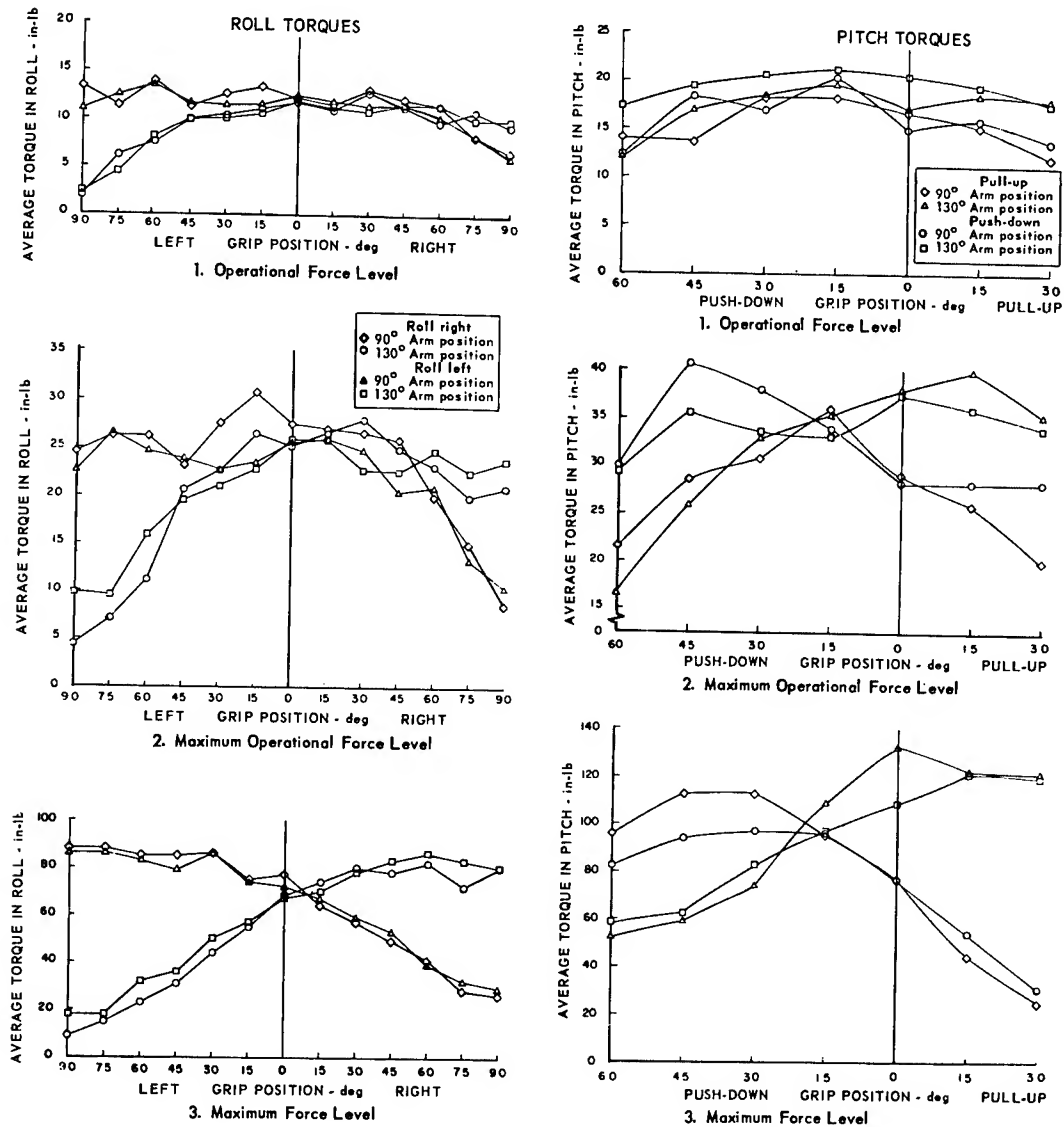


Pilot	Distance A in.			Distance B, in.		Maximum controller angle (unconstrained), deg							
						Right Roll		Left Roll		Forward Pitch		Rearward Pitch	
	Measured at elbow angle of -												
	90°	130°	180°	90°	130°	90°	130°	90°	130°	90°	130°	90°	130°
1	15.00	19.00	26.25	13.00	12.50	105	105	80	75	45	35	30	40
2	11.50	18.00	25.00	12.75	11.50	90	100	90	100	65	70	30	30
3	13.00	18.00	25.00	13.00	12.00	90	90	90	95	55	60	30	35
4	12.00	18.00	25.00	13.00	12.00	85	85	75	80	50	45	30	30
5	14.00	18.50	26.00	13.00	12.50	90	95	90	100	60	65	30	30
6	14.50	18.50	27.00	13.75	13.75	90	100	90	100	75	55	45	40
7	12.50	18.00	25.00	12.75	11.50	90	90	105	105	70	75	30	30
8	13.50	18.50	27.00	13.25	13.00	100	95	100	100	80	75	30	30
9	13.30	18.50	27.00	13.25	13.00	90	90	105	105	45	45	40	40
10	13.00	17.50	27.50	13.75	13.50	90	100	90	105	75	65	55	55
11	14.50	18.75	28.50	13.25	13.75	90	105	90	105	60	75	30	30
Average	13.35	18.30	26.30	13.15	12.63	91.8	96	91.4	97.3	61.8	60.4	34.5	35.0

Measurements of the arms of pilots using a mockup of a side-arm controller, and of the unconstrained angular deflections they could achieve in roll and pitch with the controller. Data were taken with the arm straight or flexed as shown. The preferred neutral position for the controller was found to be 8° to the right and 15° forward of the vertical. The preferred arm position was a slight forward extension from 90°.

Figure 16-13 (continued)

b.



Source: Brissenden (38)

These graphs show the forces the pilots could develop at two elbow angles. They were instructed to apply the following levels of exertion:

- (1) Operational force - chosen as the comfortable level for continuous control maneuvers.
- (2) Maximum Operational force - acceptable for short periods, applicable to any maneuver requiring maximum control capability.
- (3) Maximum force - the greatest force pilots could exert in each grip position.

Figure 16-14

Design Factors for Hand Controls in Spacecraft

a. Forces Exerted on Hand Controls

Vertical Handgrip											
N = 55											
Right Arm						Left Arm					
Direction of force	Elbow angle (deg)	5th	50th	95th	S. D.	Direction of force	Elbow angle (deg)	5th	50th	95th	S. D.
Push	60	34	92	150	38	Push	60	22	79	164	31
	90	36	86	154	33		90	22	83	172	35
	120	36	103	172	43		120	26	99	180	42
	150	42	123	194	45		150	30	111	192	48
	180	50	138	210	49		180	42	126	196	47
Pull	60	24	63	74	23	Pull	60	26	64	110	23
	90	37	88	135	30		90	32	80	122	28
	120	42	104	154	31		120	34	94	152	34
	150	56	122	189	36		150	42	112	188	37
	180	52	120	171	37		180	50	116	172	37
Left	60	20	52	87	19	Left	60	12	32	62	17
	90	18	50	97	23		90	10	33	72	19
	120	22	53	100	26		120	10	30	68	18
	150	20	54	104	25		150	8	29	66	20
	180	20	50	104	26		180	8	30	64	20
Right	60	17	42	82	20	Right	60	17	50	83	21
	90	16	37	68	18		90	16	48	87	22
	120	15	34	62	17		120	20	45	89	21
	150	15	33	64	18		150	15	47	113	27
	180	14	34	62	24		180	13	43	92	22
Up	60	20	49	82	18	Up	60	15	44	82	18
	90	20	56	106	22		90	17	52	100	22
	120	24	60	124	24		120	17	54	102	25
	150	18	56	118	28		150	15	52	110	27
	180	14	43	88	22		180	9	41	83	23
Down	60	20	51	89	21	Down	60	18	46	76	18
	90	26	53	88	20		90	21	49	92	20
	120	26	58	98	23		120	21	51	102	23
	150	20	47	80	18		150	18	41	74	16
	180	17	41	82	18		180	13	35	72	15

Source: Hunsicker (171)

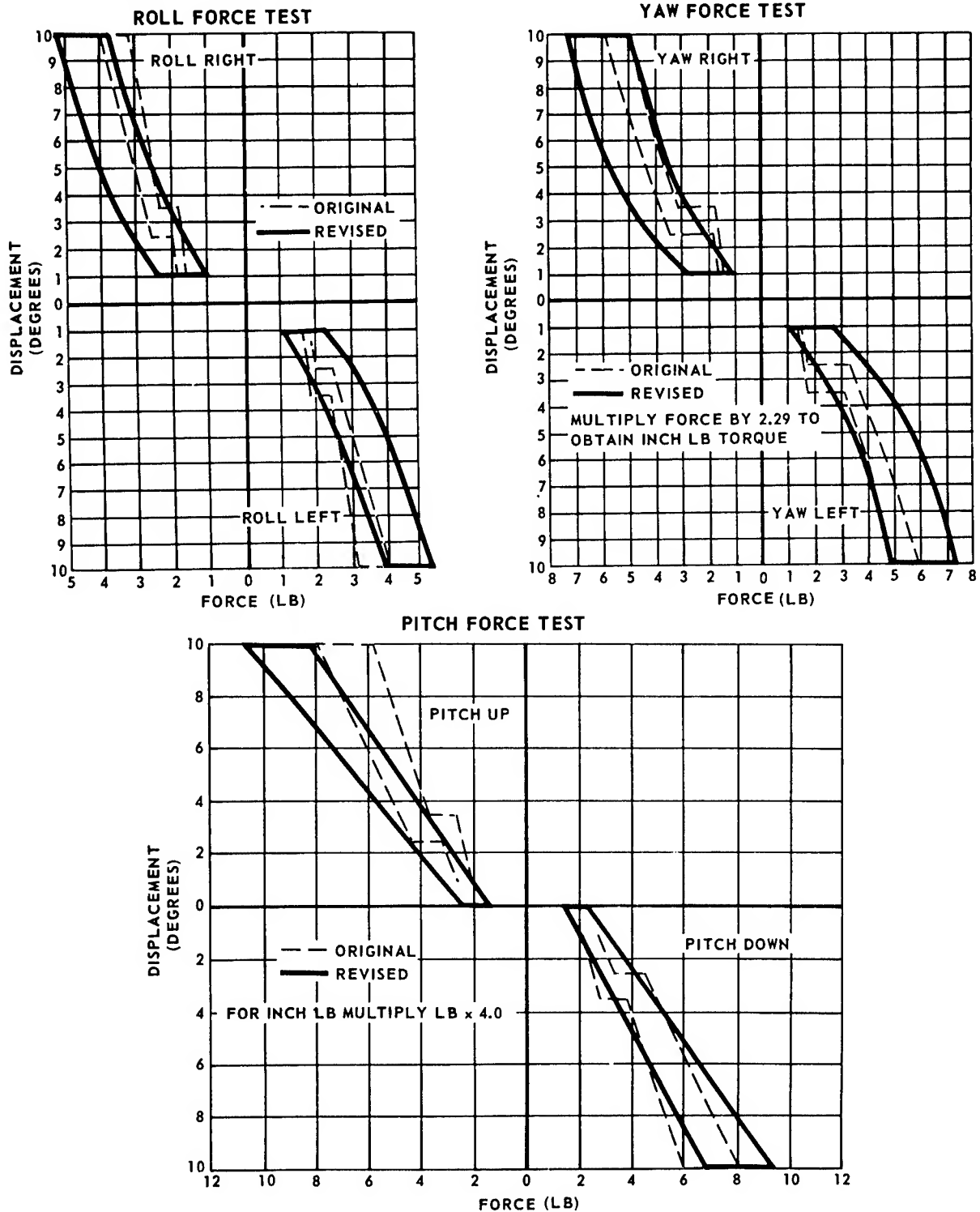
Horizontal Handgrip											
N = 30											
Right Arm--Wrist Pronated						Left Arm--Wrist Pronated					
Direction of force	Elbow angle (deg)	5th	Percentiles		S. D.	Direction of force	Elbow angle (deg)	5th	Percentiles		S. D.
Push	60	40	94	156	36	Push	60	33	86	138	35
	90	25	65	100	24		90	27	60	93	28
	120	23	46	70	15		120	17	43	71	17
	150	18	40	66	18		150	15	37	69	18
	180	17	32	59	12		180	12	32	59	13
Pull	60	13	37	50	16	Pull	60	20	39	64	18
	90	14	32	54	13		90	17	37	63	18
	120	13	26	43	10		120	12	30	56	14
	150	12	29	48	10		150	15	32	52	13
	180	11	28	48	12		180	16	34	61	15
Left	60	19	41	72	19	Left	60	20	42	66	15
	90	12	31	64	15		90	17	38	60	12
	120	9	26	53	13		120	17	34	53	8
	150	9	21	39	11		150	17	31	54	11
	180	10	19	34	7		180	15	28	41	8
Right	60	16	48	73	18	Right	60	18	36	51	15
	90	16	39	59	15		90	11	27	54	11
	120		34	47	11		120	10	22	39	10
	150	18	32	45	7		150	9	23	53	16
	180	16	31	57	13		180	10	20	49	13
Up	60	23	49	79	20	Up	60	22	57	100	22
	90	28	69	112	29		90	37	77	123	24
	120	41	91	138	30		120	45	91	145	30
	150	43	99	165	38		150	58	100	159	32
	180	35	95	158	35		180	47	101	171	
Down	60	23	61	158	35	Down	60	18	74	139	35
	90	22	83	142	35		90	23	75	136	34
	120	37	92	161	35		120	29	75	148	
	150	40	90	154	34		150	39	79	136	19
	180	41	87	143	31		180	34	76	138	31

Source: Hunsicker (172)

Controls designed to be actuated by human force should be operable by the weakest individuals of the using population but able to withstand the maximum force the strongest individuals of the using population can apply. The tables show the maximum forces (measured in pounds) exerted on vertical or horizontal handgrips by male college students, tested in a seated position.

Figure 16-14 (continued)

- b. Hand Forces for Attitude Control in the Gemini Spacecraft
(original (—) and revised (----))



d. PULSE - For each deflection of the controller away from the center position, a single short duration (20 msec) pulse was applied to the appropriate axis.

e. RATE CMD, RE-ENT - Similar to rate command with a wider neutral band and gain crossfeed from roll to yaw. (Designed for use in manual re-entry.)

f. RE-ENT - Pitch and yaw axes in rate damping control mode, with roll axis slaved to bank-angle command from the computer.

g. PLAT - ACME accepted attitude information from the platform and provided outputs to the thrusters to maintain spacecraft attitude automatically within pitch, yaw and roll deadbands.

h. PARA - A mode designed for use with a paraglider which was eliminated before the first manned flight. (On Spacecraft V and up, this selector position was used for the PLATFORM mode.)

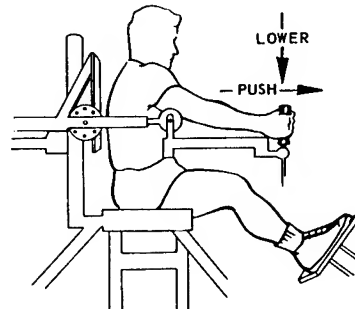
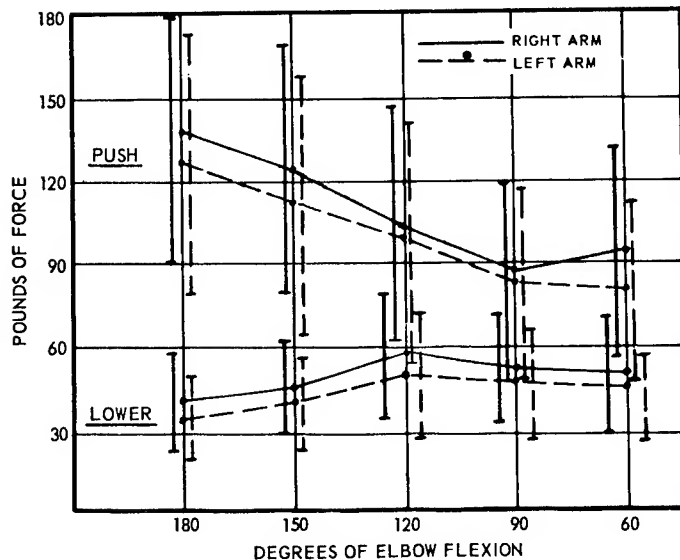
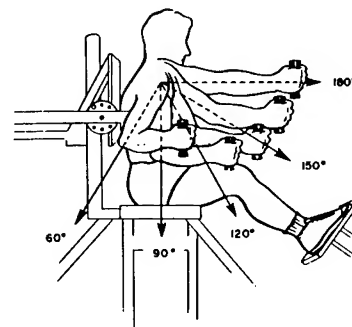
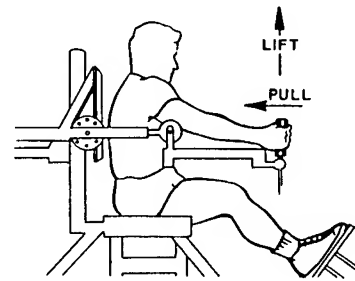
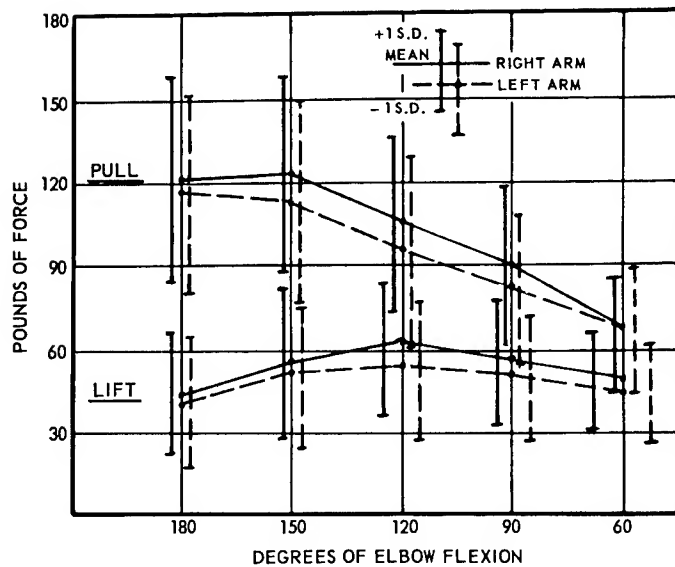
Arm strength with elbow flexion is recorded in Figure 16-15. Leg strength is recorded in Figure 16-16 and lifting strength in Figure 16-17. Cranking speeds and other motion factors for shirtsleeved males have recently been reviewed (71).

A handbook of control design for pressure-suited subjects has been published (295). Controls and displays used in Gemini have been reviewed (217, 218). Data are available on static and dynamic factors in design of wheeled vehicles for terrestrial (56) and lunar operations (132, 140); also, for manned space-simulation chambers (9, 10, 15, 58, 218, 227).

Complex motor control and integration of man into the machine control loop has received much study in relation to aircraft and spacecraft problems. Several major reviews and symposia are available (References 7-532, 7-694, 7-689) and (178, 238, 257, 262, 302, 317, 343, 345, 373). A Soviet review of this subject has also been presented (78). General assessments of optimal human performance in space systems have been made (238, 239, 292). More specific human control studies have been made of spaceflight tasks. These include: manual space navigation (242), orbital docking of large attitude-stabilized components and other systems (59, 272), lunar landing vehicles (9, 179, 205). The visual aspects of rendezvous and docking control have been reviewed on pages 2-96 to 2-108 of the section on Light, (No. 2). Finally, studies on the simulation of lunar missions with emphasis on learning and retention of complex skills have been published (69) and Reference (7-254).

Human performance in the different acceleration environments including microgravity and zero gravity has been covered in Oxygen-CO₂-Energy, (No. 10) and in Acceleration, (No. 7). Effects of training on the performance of motor skills during the Gemini EVA were reviewed on pages 7-129 to 7-154. Training plans for Apollo are available (248). Soviet studies of responses to intra- and extravehicular exercise in Voskhods I and II are now published. (See also pages 7-131 and 7-132.)

Human factors in the assembly and maintenance of large space structures are under current study (282, 372). The effects of human motions and forces on the stability of orbiting vehicles have been simulated (81, 321).



Mean values and standard deviations for the strength of pulling, lifting, pushing, and lowering with each arm and with the elbow flexed at the angles indicated, on the right. The sample group was 55 college men, selected to approximate the characteristics of aircrewmembers. Testing was done with a strain gauge dynamometer to record the forces on the isometric handgrip (which does not move appreciably).

Source: Hunsicker⁽¹⁷¹⁾, additional data may be found in Morgan et al⁽²²⁴⁾

Figure 16-15

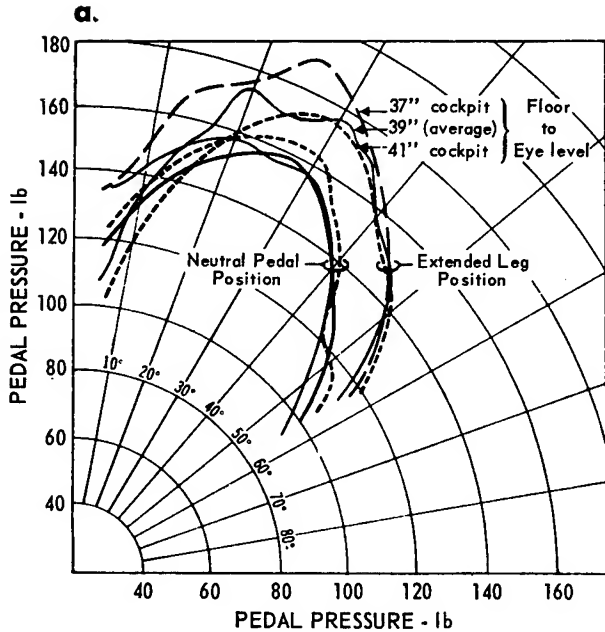
Arm Strength with Elbow Flexion

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Figure 16-16

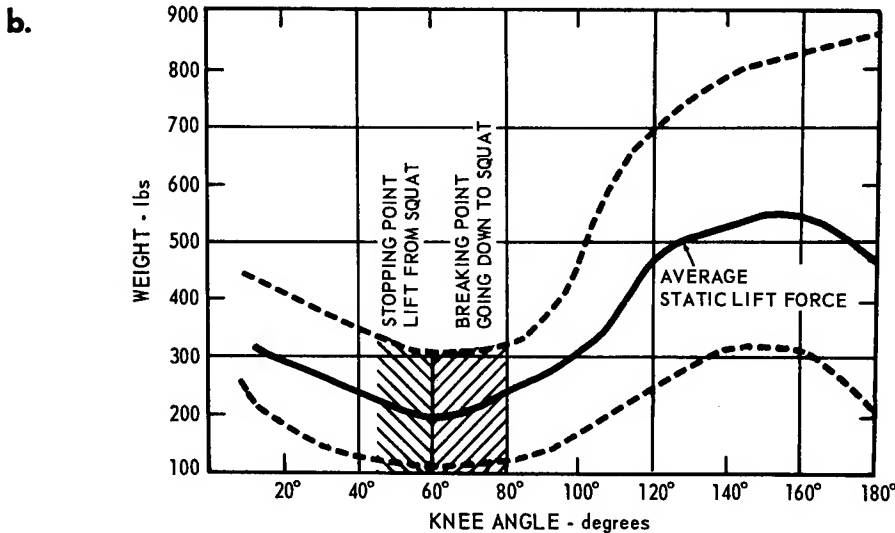
Leg Strength

(After Hertzberg and Clauser⁽¹⁶⁴⁾)



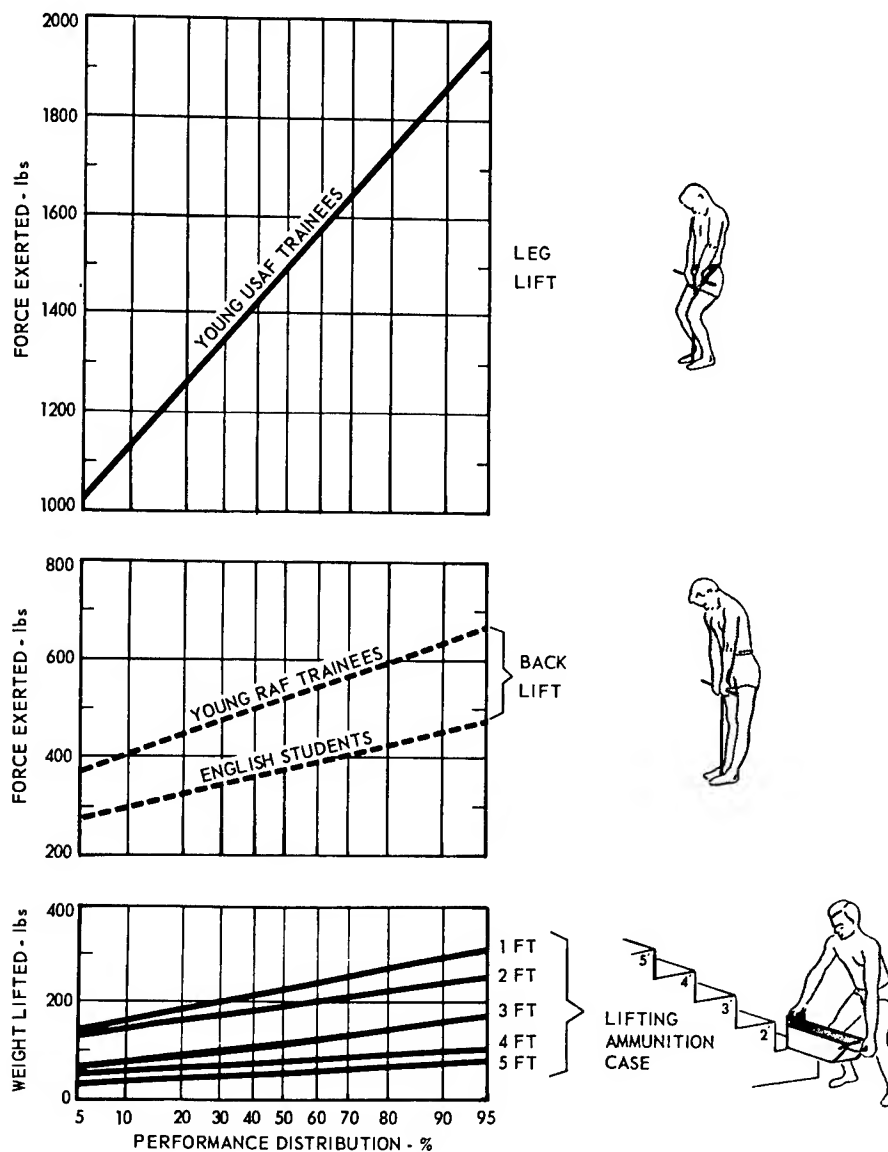
Foot rotation forces on an aircraft brake pedal measured at various angles of the brake pedal in neutral and extended leg positions. Floor to eye height was also varied from 37 to 41 inches. Data are averages of 100 subjects.

Source: Hertzberg⁽¹⁶²⁾



The static lifting forces applied against dynamometers by 13 subjects with knees variously bent as shown by the scale of knee angles. The central line shows average values, and the outer dashed line shows the range of forces. In addition, subjects were tested in dynamic lift, shown by the two shaded areas, using bar bell weights on their shoulders. Maximum rise from full squatting posture is shown in the left hand shaded bar as the maximum angle of knee extension. The right hand shaded bar shows the "angle of break," determined by starting with weights on the shoulders and a full standing position, then gradually squatting until the leg could no longer restrain the motion and a rapid downward motion began.

Source: Swearingen et al⁽³¹⁸⁾



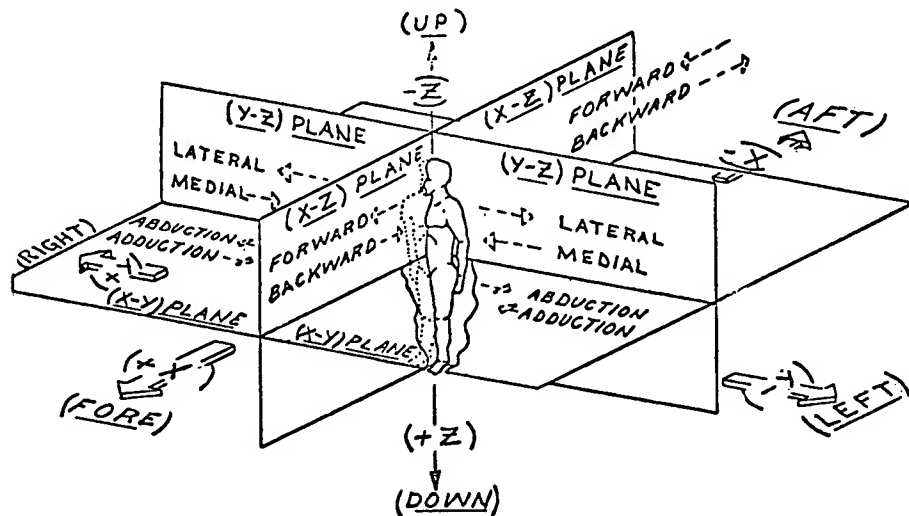
The variations in lifting strength as different lifting tasks are measured. Each of the three types of lift shown is plotted on a probability grid to show the percentile performances. Note the low values for lift when an awkward load (the ammunition case from the F-86H aircraft) must be raised. Note also the very high values when the strong leg muscles are ideally employed, as shown in the upper set labeled "Leg Lift". Here, not only the hands were used to grip the dynamometer bar; a special belt and fastener helped transfer the force to the handle. These data may be of value in planning post-landing survival maneuvers.

Adapted from Catheart et al⁽⁵²⁾, Clarke⁽⁶⁴⁾, and Emanuel and Chaffee⁽⁹⁰⁾

Figure 16-17

Lifting Strength

(After Hertzberg and Clauser⁽¹⁶⁴⁾)



Plane Definitions:

- (Y - Z Plane) - Frontal Plane
- (X - Z Plane) - Sagittal Plane
- (X - Y Plane) - Transverse Plane

Type of Limb Movement Terms:

- Flexion - Bending or decreasing the angle between parts of the body.
- Extension - Straightening or increasing the angle between parts of the body.
- Stretch - Lengthening of body part.
- Rotation - Revolution about the axis of a body part.
- Pronation - Face down.
- Supination - On back or Face up.

Direction of Limb Movement Terms:

- Forward = +X Direction
- Backward = -X Direction
- Upward = -Z Direction
- Downward = +Z Direction
- Right = +Y Direction
- Left = -Y Direction
- Lateral = Away from (X-Z) plane (in Y-Z plane)
- Medial = Toward (X-Z) plane (in Y-Z plane)
- Abduction = Away from (X-Z) plane (in X-Y plane)
- Adduction = Toward (X-Z) plane (in X-Y plane)

Figure 16-18

Terminology and Definitions for Describing the Mobility
of the Pressure Garment Assembly

(After NASA⁽³³⁶⁾)

Extravehicular Garments and Mobility

Special consideration must be given to anthropometric factors in planning extravehicular mobility. Suggestions have been made regarding critical areas in the design of the Apollo Extravehicular Mobility Unit (EMU) which consists of the following subsystems (336): Pressure Garment Assembly (PGA), Constant Wear Garment (CWG), Liquid Cooling Garment (LCG), Thermal and Meteoroid Garment (TMG), Extravehicular Visor Assembly (EVA), Portable Life Support System (PLSS), Emergency Oxygen System (EOS).

Design features should prevent impediments to astronaut in the performance of his tasks which include:

- Donning, doffing and checkout of applicable EMU subsystems within the command Module (CM) (185).
- Donning, doffing and checkout of the TMG, EVA, PLSS, and EOS within the LEM in both a pressurized and depressurized cabin (185).
- Egress and ingress through all the CM or the LM hatches in free space and/or (for LM only) on the lunar surface while carrying scientific or maintenance equipment (207, 346). (See discussion on page 16-36.)
- Descending and ascending LM vertical ladders (309).
- Walking over the lunar surface while carrying assorted tools, scientific and navigation equipment (Figure 7-73) (290, 309).
- Performing various scientific experiments on the lunar surface such as hook-up and emplacement of passive recording instruments, seismometers, geophones, radiation detection devices, magnetometers, power supplies; setup and operation of cameras, levels, transits, stud guns; collection and packaging of lunar soil specimens, etc. (115, 184, 185) (Figure 7-73).
- Performing specific mobility tasks on lunar surface, unassisted, such as crouching in a deep knee bend; kneeling on one and/or both knees; crawling forward and backward; getting up from a prone or supine position; bending and picking up small objects on the ground without kneeling (309).

Analyses of many of these tasks have been presented under performance in zero and subgravity of Acceleration, (No. 7). Intra and extravehicular activities of suited subjects in Gemini have been covered in great detail by NASA reviews (216, 231).

Pressure Garment Assemblies (Soft and Hard Suits)

The Pressure Garment Assembly (PGA) is an anthropomorphic pressure vessel encompassing the entire body. The Assembly is individually sized to the existing astronaut population (Figure 16-4). The PGA is tailored as close as possible to actual body contours and to necessary internal PGA components

and should provide break points at natural body break-points to enhance mobility and reduce excessive bulk. The crewman should be comfortable in a pressurized PGA, fully restrained in the Command Module couch under the effect of a sustained acceleration of 5 g's, +G_x, eyeballs in. It has been recommended that the following exterior dimensions not be exceeded:

1. Across shoulder: 23-3/4 inches;
2. Across elbows: 23-3/4 inches;
3. Across knees: 16 inches.

The combined center of gravity of the PGA and the crewman should be located within two (2) inches vertically and one (1) inch horizontally of the CG of a nude, standing crewman as noted in Figures 16-6, 16-7, and 6-11.

The mobility requirements for the PGA are described in terms of the terminology and definitions provided in Figure 16-18. The types of mobility of concern to PGA design include the following:

- Elementary movements, or movements of the body, limbs, or head in one plane.

- Complex movements, which are movements of the arms, wrists, hands and fingers which require a high degree of psychomotor coordination and movement in more than one plane (295).

- Total body movements, which include movements involved in walking, lifting objects, etc.

- Suit equilibrium positions, which are positions the garments tend to seek when no torque is being applied to the joints.

The movements of the head, body, limbs, and/or elementary movements, which the astronaut should be capable of performing with the PGA vented or pressurized to $3.7 \pm .2$ psi are indicated in Table 16-19. This table indicates the minimum range of movement in degrees for each of the movements and the maximum torque in inch-pounds (or foot-pounds) required to initiate and sustain the movement.

The complex movements of the arms, wrists, hands, and fingers which the Apollo crew should be capable of performing both extravehicularly and intravehicularly with the suit pressurized to $3.7 \pm .2$ psig are indicated in Tables 16-20 to 16-22. The coordinated movements of the torso, arms, legs, hands, feet, and head such as are required during lunar surface operations and during the extravehicular phase of orbital flight with the suit pressurized between 3.5 and 3.9 psig are indicated in Tables 16-22 a and b. Data for the design of equipment and altered movement patterns resulting from zero gravity have been covered in the section on zero gravity in Acceleration (No. 7).

As general anthropomorphic factors in the design of extravehicular garments, the following have been suggested (336). If equilibrium positions exist for the garments, i. e., positions into which the garments will spring to or seek if no restrictive force is applied by the crewman in the EMU, they

Table 16-19

Maximum Performance Requirements for the Elementary Body Movements
Intravehicular and Extravehicular Wear, Vented or at 3.7 Psia

(After NASA-CSD-A-096(336))

MOVEMENTS	RANGE OF MOVEMENTS (In degrees)	MAXIMUM TORQUE REQUIRED
A. NECK MOBILITY		
Flexion (forward-backward)	120	0
Flexion (left-right)	30	0
Rotation (Abduction-Adduction)	140	0
B. SHOULDER MOBILITY		
Adduction	45	1 ft. lb _f
Abduction	125	1 ft. lb _f
Lateral - Medial	150	1 ft. lb _f
Flexion	170	1 ft. lb _f
Extension	50	1 ft. lb _f
Rotation (X-Z Plane)		
Down-up	135	1 ft. lb _f
Rotation (Y-Z Plane):		
Lateral Rotation	35	1 ft. lb _f
Medial Rotation	95	1 ft. lb _f
C. ELBOW MOBILITY		
Flexion - Extension	140	1 ft. lb _f
D. FOREARM MOBILITY		
Supination (Palms up)	90	.2 ft. lb _f
Pronation (Palms down)	75	.2 ft. lb _f
E. WRIST MOBILITY		
Palmar Flexion	75	.2 ft. lb _f
Dorsiflexion	65	.2 ft. lb _f
Abduction	50	.2 ft. lb _f
Adduction	30	.2 ft. lb _f
F. TRUNK - TORSO MOBILITY		
Trunk Rotation (abduction - adduction)	70	2 ft. lb _f
Torso Flexion (lateral - medial)	50	2 ft. lb _f
Torso Flexion (forward)	90	2 ft. lb _f
Torso Flexion (backward)	25	2 ft. lb _f
G. HIP MOBILITY		
Abduction (leg straight)	45	2 ft. lb _f
Adduction (knee bent)	30	2 ft. lb _f
Abduction (knee bent)	35	2 ft. lb _f
Rotation (sitting):		
Lateral	30	2 ft. lb _f
Rotation (sitting):		
Medial	30	2 ft. lb _f
Flexion	115	2 ft. lb _f
Extension	35	2 ft. lb _f
H. KNEE MOBILITY		
Flexion (standing)	110	1 ft. lb _f
Rotation (medial)	35	1 ft. lb _f
Rotation (lateral)	35	1 ft. lb _f
Flexion (kneeling)	155	1 ft. lb _f
J. ANKLE MOBILITY		
Extension	40	3.0 ft. lb _f
Flexion	35	3.0 ft. lb _f
Abduction	25	3.0 ft. lb _f
Adduction	25	3.0 ft. lb _f

Table 16-20

Elemental Movements of the Wrist, Hands, and Fingers
Required in Apollo EMU Operations

(After NASA-CSD-A-096⁽³³⁶⁾)

Movements or Operations	Description of Performance	Intravehicular		Extravehicular
		0.18 PSIG	3.5-3.9 PSIG	
Palmar	Write legibly with pencil	x	x	x
	Operate .375" dia. rotary knob	x	x	x
	Utilize small screwdriver	x	x	x
Tip Prehension	Pick up small objects as:			
	- Small screws	x	x	
	- Small rocks			x
Lateral Prehension	Operate 2 and 3 position space-			
	craft toggle switches			
	- Vertically	x	x	x
	- Horizontally	x	x	x
Grasp	Use a screwdriver	x	x	x
	Use pliers	x	x	x
	Use crescent wrench	x	x	x
	Use socket wrench	x	x	x
	Use hand-controller	x	x	
Finger: Pushbutton Ops.	Operate pushbutton within panel of pushbuttons	x	x	x
Finger: Pulling Ops.	Operate T-handle control	x	x	x
	Operate D-handle control	x	x	x
	Operate ring handle control	x	x	x
Thumb	Operate thumbwheel	x	x	x
	Operate button on control handle	x	x	
Hand Rotation	Operate discrete position rotary switch	x	x	x
Wrist Movements	Move wrist side to side while opening and closing fingers	x	x	x
	Move wrist up and down while opening and closing fingers	x	x	x
Whole Hand Movement	Hold hand at any desired position	x	x	x

Intravehicular wear = CWG and PGA
or
LCG and PGA

x = required

Table 16-21

Movements of the Wrist, Hands, and Fingers Related to the Intravehicular Operation
of the Pressure Garment Assembly in Apollo

(After NASA-CSD-A-096⁽³³⁶⁾)

Components of PGA Defining the Complex Movements Requirements	0.18 PSIG (Suit Ventilated)			*	3.5-3.9 PSIG		
	CM (Couch Pos.)	CM (Vert. Pos.)	LEM (Vert. Pos.)		CM (Couch Pos.)	CM (Vert. Pos.)	LEM (Vert. Pos.)
1. Helmet Ring Disconnect	x	x	x				
2. EV Visor Positioning							
3. EV Visor Attachment			x				x
4. Medical Injection Fitting	x	x	x	x	x		x
5. PLSS Controls and Attachments		x	x		x		x
6. EOS Controls		x	x				
7. Multiple Gas Disconnect	x	x	x	x	x		x
8. WMS Disconnect	x	x	x	x	x		x
9. Multiple Water Disconnect		x	x		x		x
10. Electrical Disconnect	x	x	x	x	x		x

x = required

* Provided there is no interference from the restraint harness.

Table 16-22

Complex Total Body Mobility Requirements Required for Intravehicular and Extravehicular
Phases of Apollo at 1/6 G and Zero G

(After NASA-CSD-A-096⁽³³⁶⁾)

a. Total Mobility Performance Criteria at 1/6 G, PGA Pressurized to 3.5 to 3.9 Psig

1. Climb ladder at slopes up to 27° with rungs spaced every 8 inches.
2. Remove equipment from LEM with LEM at 27° position.
3. Crouching in a deep knee bend for three minutes.
4. Kneeling on one knee for five minutes and working in kneeling position.
5. Crawling forward 5 feet, then backward to starting point.
6. Getting to and up from supine and prone positions (unassisted) within 30 seconds.
7. Pickup and carry 2nd astronaut.
8. Walking erect on 3° inclined treadmill at 3 mph for 10 minutes; jumping over small crevices; taking long strides.

Table 16-22 (continued)

a. Total Mobility Performance Criteria at 1/6 G, PGA Pressurized to 3.5 to 3.9 Psig (cont.)

9. Bending over to reach and pick up small objects on ground without the necessity of kneeling.
10. Operate PLSS controls.
11. Moving from standing erect to sitting position (unassisted) without making suit adjustments.
12. Lift without squatting.
13. Donning extravehicular wear with assistance, as necessary, while pressurized. This includes:
 - a. External Thermal Garment (ETG) (including boots, garment
 - b. and supplementary visor)
 - c. Meteoroid Protection Garment (MPG)
 - d. Portable Life Support System (PLSS)
 - e. Emergency Oxygen System (EOS)
14. Forward reach while in kneeling position and torque at distance obtained.
15. Crawl face up or down thru LEM access hatch.
16. Capability to bend down in LEM and shut and lock LEM hatch.
17. Operate overhead hatch.
18. Change LiOH canisters.
19. Handle equipment in torso-bent position in restricted area.
20. Self donning PLSS.

b. Complex Mobility Performance Criteria at Zero G

-
1. Operate stem unit (transfer).
 2. Handle equipment and carry out tunnel transfer.
 3. Don Extravehicular Mobility Unit
 4. Work at navigation and Guidance Consoles in the Command and Lunar modules.
 5. Handle Portable Life Support System in Lunar module
 6. Access to Command Module lower equipment bay and capability to handle equipment.
 7. Capability to carry out couch operations in Command Module.
 8. Capability to carry out free space transfer.
-

should correspond as closely as possible to the "natural" position for each related task. Design should be compatible with the quick donning requirements. Closing and sealing operations should be possible without requiring assistance and/or while donning in the dark. Design should permit donning within a single time period of at least fifteen minutes without assistance in an illuminated CM while at zero gravity. Design of elastic and foamed garments to replace pressurized suits has been suggested (161, 270, 346).

The following features may act as aids to facilitate donning of the PGA:

- Non-bunching, low bulk, inner layers which are resistant to dimensional buildup.
- Smooth inner surface containing no pockets, flaps, or discontinuities.
- Incorporation of positive alignment devices for engaging mating parts.
- Minimum number of components requiring connections prior to pressurization.
- Positive indications of correct installation of mating parts.
- Engagement of a locking latch at the neck should be accomplished with a force of no more than 10 pounds.

Within the pressure garment, the liquid cooled garment, LCG, should be a moderately form-fitting flexible garment encompassing the entire body with the exception of the head and hands. (270) It should resist bunching, not bind or restrict the crewman or cause pressure points, and be constructed of absorbent loose weave material to permit capillary wicking of body moisture for evaporation. The flexible liquid coolant tubes should be located in a pattern which assures intimate contact with the typical astronaut skin surface at all times. (See section on liquid-cooled garments in Thermal Environment No. 6).

In the Apollo program it is planned that the Thermal-Meteoroid Garment (TMG) will encompass the entire EMU with the exception of the PLSS and the helmet assembly which will incorporate separate thermal and meteoroid protection (270). The TMG will consist of a parka, trousers, a pair of lunar boots and a pair of mittens. It will be conformal to the PGA and not contain excessive material which may cause folds or bunching. The outer layer of the TMG will be abrasion resistant, particularly in the area of the knees. The performance of the TMG should not be altered by adhesion of lunar dust. Provision should be made for the attachment of indicators and dosimeter devices in the areas which are readily accessible to the crewman during the lunar surface mission. Access should be permitted to the intravehicular-extravehicular controls, displays, connectors, and adjustment devices while in a pressurized PGA as noted in Tables 16-19 and 16-20. Design of the meteoroid garment of Gemini is covered in Pressure (No. 12) and reference (216). Data for the design of radiant insulations of the TMG are covered in Thermal Environment (No. 6); and for meteoroid protection, in Pressure, (No. 12).

A detailed analysis of the several different Gemini suits has been published (217). Data are also available on current prototype suits. The range of weight, volumes, mobilities and visual fields attained in prototype Apollo suits are

covered in Table 16-23 (75, 185, 206, 270). Table 16-23 a and b review component weights of the soft and hard suits. Table 16-23 c gives the gaseous volumes of individual components of hard and soft suits (276). The residual volumes of Table 12-19 represent the volumes remaining in the suit after dis-
 aption of major seals. The total gaseous volume of a typical soft suit and LSS (excluding respiratory tract of the astronaut) is 28 liters. The gaseous volume of the soft-suit helmets vary from 2 to 3 liters. The total gaseous volume of a typical hard suit and back pack is about 75 liters. The helmet of the hard suit is a hemisphere of about 12 inches in diameter. The total volume of the helmet is about 7400 cc; the volume of the head, about 3000 cc; and the free gaseous volume inside the helmet, about 4400 cc. Table 16-23c also gives the orifice areas at major seals and cross section areas of the body seal sites. These data can be used for calculating pressure decay curves during explosive decompression (276).

Figures 23-d and e cover range of mobilities for 3 different soft suits. Wearing the LCG, the test subject was appropriately positioned and restrained in the mobility-notation table, and the angular excursion for the following move-
 ments were obtained for the unsuited, vented, and pressurized (3.7 psig). Figure 12-23 e presents data on restriction of movement relative to the nude. Using these data, and a weighting system developed for this study (185) the space suits were rated as follows: In the vented condition, suit C ranked first, suit A second, and suit B third; pressurized to 3.7 psig, suit A ranked first, suit C second, and suit B third. In a final rating for the angular-range study, suit C ranked first, suit A second, and suit B third. After studying the strob-
 copic motion series and viewing the movies of mobility sequences, the three space suits were rated by the evaluation team. For the 3.7 psig condition, with and without the TMG, suit A was ranked first, suit C second, and suit B third. The two evaluations (angular-range study along with the strobe and movie sequences) were considered together in arriving at a final rating on general mobility. Since the strobe and cine sequences included a broader

Table 16-23

Range of Weights, Volumes, Mobilities, and Visual Fields
 Attained in Prototype Apollo Space Suits

a. Component Weights of Prototype Apollo Soft Suits (in grams and pounds)

Type of suit	Helmet with communications	Gloves, pair	Limb-torso suit	PGA (a)	EV Visor assembly	Water garment	Constant wear garment
Suit B	1865 4.10	494.5 1.89	10 870 2.38	13 229.5 29.2	1325 2.94	1483 3.26	268 .59
Suit A	1216 2.68	638 1.40	10 590 23.3	12 444 27.4	1007 2.22	0	0
Suit C	1203 2.65	649.5 1.43	8 730.5 19.3	10 583 23.3	1169.5 2.57	^b 1029.5 2.26	312 .69

^aWeight of PGA represents sum of weights for helmet, gloves, and limb-torso suit.
^bWeight included no connectors.

(After Jones⁽¹⁸⁵⁾)

Table 16-23 (continued)

b. Weight of Hard Suit Components (in pounds)

<u>Component</u>	<u>RX-2A</u>	<u>RX-3 Goals</u>	<u>Current Estimates</u>	<u>Micrometeoroid Protection (Honeycomb Layup)</u>
Helmet and Sun Visor	3.67	4.5	5.0	0.5
Gloves	1.30	1.0	1.0	-
Wrist Joints	-	1.0	1.6	-
Lower Arm	1.04	1.2	1.4	0.2
Elbow Joints	2.80	1.0	1.0	-
Upper Arm	2.30	2.0	2.4	0.2
Shoulder Joints	7.34	6.4	6.4	-
Torso, Upper	9.85	4.8	4.8	0.1
Torso, Lower	5.80	5.2	5.2	0.1
Waist Joint	6.26	5.1	5.1	0.1
Body Seal Mechanism	4.76	1.5	1.5	-
Pants	3.94	2.9	2.9	0.1
Thigh Joints	10.52	8.0	8.4	0.9
Knee Joints	5.48	3.6	3.6	-
Calves	3.24	3.0	3.0	1.4
Ankles	3.40	1.0	2.2	-
Boots	4.08	3.0	3.0	-
Internal Pads and Ducting	4.37	2.8	2.8	-
Misc. (Head rest — inter-com, connec- tors, etc.)	-	2.0	2.0	-
Total	80.15	60.0	63.3	3.6

RX-3 Suit Weight minus Micrometeoroid Protection - 59.7

Shoulder Breadth of Both Suits - 23 inches

Leakage Rate - 25 Scc/min (2.1×10^{-3} cfm)

Maximum Joint Torque - 0.28 m-kp (2.0 lb-ft)

(After Litton Industries⁽²⁰⁶⁾)

Table 16-23 (continued)

c. Effective Volumes and Orifices During Explosive Decompression
of Soft and Hard Space Suits by Seal Disruption

<u>Critical Volumes</u>	<u>Apollo Soft Suit</u>	<u>Apollo Hard Suit</u>
Total free volume of suit, PLSS, and hoses	28 liters	75 liters
Free volume of helmet	~2.5 liters	4.4 liters
Free volume in PLSS and hoses (2 hoses, 3/4" ID, and 2 1/2 feet and 6 feet long)	3.8 liters	3.8 liters
Free volume of suit below neck ring	22 liters	67 liters
<u>Neck Seal</u>		
Diameter of seal	9" ID	11.8" ID
X-area	411 cm ²	706 cm ²
Angle of elevation of seal	17°	40°
X-area of neck subtended by seal	116 cm ²	145 cm ²
Orifice at neck seal	295 cm ²	561 cm ²
<u>Wrist Seal</u>		
Diameter Seal	4" ID	3.87" ID
X-area of seal	81.4 cm ²	76 cm ²
X-area of wrist at seal	21.5 cm ²	21.5 cm ²
Orifice at wrist seal	60 cm ²	54 cm ²
<u>Thigh Seal</u>		
Diameter	-	(RX 4 and 5) 7 7/8"
X-area seal	-	314 cm ²
X-area of lower thigh	-	137 cm ²
Orifice of thigh seal	-	177 cm ²

(After Roth (276))

Table 16-23 (continued)

c. Effective Volumes and Orifices During Explosive Decompression
of Soft and Hard Space Suits by Seal Disruption (cont.)

	<u>Apollo Soft Suit</u>	<u>Apollo Hard Suit</u>
<u>Ankle Seal</u>		(RX 3 and 4 only)
Major axes of ellipse	-	5 9/16" and 7 5/32"
X-area of seal	-	207 cm ²
Ankle area (6 1/2" from ground)	-	39 cm ²
Orifice at ankle seal	-	168 cm ²
<u>Waist Seal</u>		
Diameter	-	16" ID
X-area of body seal	-	1300 cm ²
Area of abdomen (1" above umbilicus)	-	490 cm ²
Orifice at waist seal	-	810 cm ²
<u>Fingers</u>		
Diameter of glove finger	1" ID	1" ID
X-area of glove finger	5.1 cm ²	5.1 cm ²
X-section of finger (1/16" clearance)	3.9 cm ²	3.9 cm ²
Orifice at finger	1.2 cm ²	1.2 cm ²
<u>Gas Umbilical Hose from Space Chamber</u>		
Diameter	1 1/4"	1 1/4"
X-area	7.9 cm ²	7.9 cm ²
<u>Gas Umbilicals from PLSS</u>		
Diameter	3/4"	3/4"
X-area per hose	2.8 cm ²	2.8 cm ²

Table 16-23 (continued)

d. Summary of Mobility Table Analysis of 3 Prototype Apollo Soft Suits

Movement a.	Nude base- line, deg	Angles of excursion						Percent of motion: nude to vent and vent to 3.7 psig					
		Suit C		Suit A		Suit B		Suit C		Suit A		Suit B	
		Vent	3.7 psig	Vent	3.7 psig	Vent	3.7 psig	N to V (b)	V to P (c)	N to V (b)	V to P (c)	N to V (b)	V to P (c)
1. Forearm, supination-pronation	180	194	175	168	179	180	180	100	90	93	100	100	100
2. Wrist, flexion-extension	160	178	132	140	125	146	132	100	74	87.5	89	91	90
3. Hip, adduction-abduction	180	41	32	35	15	40	35	23	78	19.4	43	22	87.5
4. Hip, flexion-extension	120	90	40	80	65	70	62	75	45	67	81	58	89
5. Shoulder, flexion-extension	250	216	190	182	168	160	139	86.5	88	73	92	64	87
6. Shoulder, frontal plane, adduction-abduction	155	115	95	125	117	80	86	74	83	81	94	52	100
7. Shoulder rotation	160	170	204	185	165	164	150	100	100	100	89	100	91
8. Elbow, flexion-extension	150	167	106	162	150	145	127	100	63	100	93	97	88
9. Wrist-forearm, flexion-extension	120	125	112	105	89	98	105	100	90	87.5	85	82	100
10. Hip, rotation	133	130	101	125	106	126	78	98	78	94	85	95	62
11. Ankle, flexion-extension	78	79	82	70	56	68	70	100	100	90	80	87	100
12. Trunk, rotation	100	70		60		48		70		60		48	
13. Shoulder, transverse plane, adduction-abduction	193	168	121	112	102	118	132	87	72	58	91	61	100
14. Knee, flexion-extension	140	160	125	143	145	135	130	100	78	100	100	96.5	96
15. Foot, flexion	43	53						100					
16. Trunk-hip, flexion-extension	68	80		44		54		100		65		79	
17. Trunk-hip, lateral flexion	78	50		32		16		64		41		21	

^aSeventeen movements are described in the paragraph entitled "Angular range study" in Ref.(185).

^bNude measures compared with vent measures.

^cVent measures compared with pressurized measures.

(After Jones⁽¹⁸⁵⁾)

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Table 16-23 (continued)

e. Angular Data for Restriction of Pressurized Joint Mobility and Suit-Joint Interface of Three Prototype Soft Suits Relative to the Nude Condition

Movement	Suit C				Suit A				Suit B			
	Nude	3.7 psig	Diff.	Percent at 3.7 (a)	Nude	3.7 psig	Diff.	Percent at 3.7 (a)	Nude	3.7 psig	Diff.	Percent at 3.7 (a)
Wrist Adduction	37	24	13	64.8	34	34	0	100	30	24	6	80.0
Abduction ^b	40	48	-8	120	34	42	-8	123.5	35	30	5	85.6
Dorsiflexion	62	56	6	90.3	63	57	7	90.4	75	68	7	90.6
Palmar flexion	87	68	19	78	60	56	4	93.3	70	53	17	75.7
Elbow Flexion	152	122	30	80.2	153	137	16	89.5	151	122	29	80.8
Extension ^c	--	--	--	--	0	5	-5		7	11	-4	157.0
Shoulder Neutral lateral	0	-10	-10		-4	-7	3		-18			
Neutral (front view)	11	39	28	35.5	4	20	16			35		
Abduction	158	83	75	52.5	167	125	42	74.8	146	78	68	53.4
Flexion	163	92	61	56.4	189	136	53	71.9	145	63	82	43.4
Extension	66	65	1	98.4	83	47	36	56.6	59			
Hip Flexion	99	57	42	57.5	123	55	68	44.7	114	58	56	50.9
Knee Neutral position	-4	-2	2	50	-2	20	22		3	3	0	100
Flexion ^c	130	93	37	71.5	96	--	--	--	95	87	8	91.5

^aPercent of motion retained in the pressurized state (percent of nude).

^bThis measure will be repeated at a later date.

^cThis measure is, as yet, incomplete.

(After Jones⁽¹⁸⁵⁾)

f. Mobility Ranges at 5 Psia Pressurization and Other Performance Data on the Apollo Hard Suit

These data represent the mobility ranges of each of the articulations provided by the Apollo Chamber Suit. These limits are achieved at torque levels under 2 ft-lbs. in every case.

Shoulder Mobility	% of Nude Range	Maximum Range
Adduction	73	35°
Abduction	90	120°
Lateral/Medial	89	108°
Flexion	87	123°
Extension	62	38°
Rotation/Lateral	100	35°
Medial	100	120°
<u>Waist Mobility</u>		
Flexion	90	40°
Side-to-Side	95	±15°
<u>Hip Mobility</u>		
Flexion	80	90°
Extension	60	10°
Abduction	38	20°
<u>Knee Mobility</u>		
Flexion	88	140°
<u>Ankle Mobility</u>		
Adduction/Abduction	85	±20°
Flexion/Extension	96	±35°
<u>Elbow Mobility</u>		
Flexion	85	120°
<u>Wrist Mobility</u>		
Adduction/Abduction	81	±30°
Flexion/Extension	64	±60°
Rotary Motion	100	360°

LEAK RATE. 30±10 scc/min, unaffected by repeated donnings and doffings. OPERATING PRESSURE. Design operating pressure is 5 psia; however normal operation is assured within the 3.5-7.0 psia range accommodating an atmosphere, 100% oxygen...or mixed gases at the higher pressure. CENTER OF GRAVITY. The center of gravity of the suit complements that of the human occupant assuring stability throughout the entire mobility range. DON/DOFF CAPABILITY. Self donning and doffing can be accomplished within 60 second periods.

(After Litton Industries⁽²⁰⁶⁾)

Table 16-23 (continued)

g. Barehand Sums Compared with Soft-Suited Raw Scores
on the Purdue Pegboard Hand Dexterity Test

	Right hand		Left hand		Both hands		Sum of scores on all hands		Assembly	
	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)	Score	Percent (a)
Barehanded (Optimal performance)	108	100	111	100	80	100	299	100	253	100
Vented										
Suit C	68	62.96	66	59.46	45.5	56.88	179.5	60.03	106	41.90
Suit B	76	70.37	78	70.27	52	65.00	206	68.90	133	52.57
Suit A	75	69.44	75	67.57	55	68.75	205	68.56	146	57.71
Pressurized										
Suit C	33	30.56	36	32.43	18	22.50	87	29.10	45	17.79
Suit B	49	45.37	49	44.14	32.5	40.63	130.5	43.65	79	31.23
Suit A	57	52.78	48	43.24	33.5	41.88	138.5	46.32	82	32.41

^aPercent of performance retained.

The differences were analyzed by the Kruskal-Wallis one way analysis variance. Analysis of the four parts of the pegboard test indicated that the difference was significant at 0.01 level in all cases except in the left-hand and both-hands test sequences under the vented condition. The both-hands test was significant at the 0.05 level, and the left-hand test was significant at the 0.10 level.

(After Jones⁽¹⁸⁵⁾),

range of mission-related movements, this portion of the test received a high weighting. In the final rating on general mobility, suit A placed first, suit C second, and suit B third.

For the strobe and cine sequences, suit A showed a clear superiority over the other two suits for pressurized mobility, both with and without the TMG. The arm and shoulder mobility was particularly good; and the subject could hold his hands over his head, relaxing and allowing his arms to remain elevated without having to fight a severe torque to keep them there. Hip flexion was also particularly good, for the pressurized subject could raise his leg more than 1 to 20 inches without leaning back and swinging around sideways to carry out the maneuver as was necessary in the other two suits. A factor of considerable significance was the ease and smoothness of motion carried out with suit A during pressurized mobility. The other two suits did not allow this ease of motion. The mobility concepts manifested in suit A have the most developmental impact. However, it would appear that an ankle joint would add much to walking, and an improvement in wrist stability and mobility is certainly needed. In addition, a method of allowing torso-bending should be investigated. Another factor to be considered is the improvement in pressurized shoulder mobility brought about by the suit C TMG top. An increase of 54° in shoulder flexion-extension and an increase of 62° in shoulder rotation were noted when data were compared with the suit B TMG top. While there is a great deal of improvement

to be made in the area of pressurized mobility in the TMG, it is noted that this concept has a great deal to offer, and it was recommended that further developmental study be carried out to improve the concept. Data are also available on the eye-heart angle in the pressurized state on contour couches (185). Data are available on the reach capabilities of prototype soft suits along all the complex planes (185).

Table 16-23 f gives the mobility restriction and other performance data for the Rx-3 hard suit.

Gloves and Boots

The intravehicular glove should be a conformal flexible envelope designed to promote hand dexterity, high tactile sensitivity, mobility, and free articulation of the hand and wrist when pressurized (270). Adequate restraint should be available to maintain normal curvature at the palm area, to prevent ballooning and the resultant loss of hand mobility. The restraint elements utilized should be located such that the glove's lines of greatest articulation will closely correspond to the natural bending lines of the palm and the fingers. Mobility features and glove restraints should be compatible with dimensional changes in the hand, such as foreshortening of the palm and lengthening of the back of the hand for clenching; or changes in surface length due to differences in band radius, as in bending the wrist. The design of the glove must be such that when pressurized or unpressurized, it will allow the crewman to realize the mobility described in Table 16-20 without fatigue, strain or discomfort. The size, flexibility and materials of the glove should be such as to enable the wearer to perform all tasks required for spacecraft operations (295), and provide for the abrasion and scuffing which results from the use of the hand and fingers within the spacecraft. If possible, the intravehicular glove should incorporate a removable GFE fingertip lighting system for each glove. The fingertip lighting system should consist of light sources to be installed on the back tip of the index and second finger of each glove.

In the design of the pressure retaining extravehicular gloves provided for use with the PGA during all extravehicular operations, thermal and abrasion protection are foremost problems. The gloves should allow the wearer free articulation of the hand for motions described in Table 16-20 and should not restrict the crewman's dexterity or tactility in performing emergency and maintenance tasks, in manipulating intravehicular and extravehicular task equipment, and in performing the tasks proposed (181, 295, 372). Especially important is facility in operation of PLSS controls during normal and emergency operation. (See Table 16-21). The gloves and fasteners used for attaching the PLSS to the PGA should be designed such that they can be fastened or unfastened with one hand.

Thermal limits for finger pain in glove design have been covered in Thermal (No. 6).

Glove and boot design in the Gemini extravehicular program has been recently reviewed (217). Hand dexterity data are available on the Apollo soft-suit prototypes. The Purdue Pegboard Test was administered to the suited test

subject in the vented and pressurized (3.7 psig) suit conditions. During two sessions of testing, six trials per suit were given for each of the two suit conditions. The test conductor turned the pegboard 180° for all trials so that wrist and finger mobility, rather than arm-reach mobility, was the influential factor. The subject was also given six trials of the test while he was bare-handed, and these data were considered to represent optimal performance.

Table 16-23g shows a comparison between barehand (optimal = 100 percent) performance and the performance retained with each suit under each condition. The fourth column of this table is the combined score of the three preceding test sequences in which only pins were used. This comparison shows clear differences in the performances of the three suits.

Ratings placed suit A in first place, suit B in second, and suit C in third. Suit C allowed considerably less wrist and finger dexterity than either of the other suits. The reduction in dexterity from the barehand level, a reduction applying to all the suits, had several causes. Fingertip lights were detrimental especially in suit C. Also, the gloves of suit C were the thickest and most cumbersome. On this suit, the wire fingernails in the thumb of the left glove came loose and interfered with test performance, and the gloves cut the subject's knuckles. Since fingertip lights interfered with hand dexterity, it was recommended that the placement of these lights be improved. The concept of fingernails on the gloves appears worthy and should be developed further, but definite improvement is necessary because the fingernails on the gloves of suit C became bent and actually interfered with dexterity. Another factor needing further development is the thickness of the material encasing the fingers. The thin material used in the gloves of suits A and B showed definite advantages over the thick material in the fingers of suit C.

Placement of the palm-restraint device should be optimized in order to allow the hand to bend below the knuckles. If the restraint device is too high and near the fingers, the subject is unable to grasp and can only flex the upper part of the fingers. Wrist stability should also be improved in all gloves, especially in the gloves of suits A and C.

All of the gloves produced pressure points at the base of the thumb and on top of the hand. These pressure points brought about excessive tiring of the hand and forearm, and induced cramping in the thumb and forearm. Consequently, considerable developmental work is needed to improve the gloves, because none of these gloves would meet the multiplicity of requirements involved in long-term pressurized wear.

Optimum design of footwear for lunar and planetary operations is now under study. (See Ref. 10-2111 for review of soil factors.)

Helmet and Visors

The optical aspects of helmet and visor design have been covered in Light (No. 2). Anthropomorphic factors must also be considered. Data on the Gemini helmet and visor systems are available (217, 231). The following are recommendations made for the Apollo program (336). The crewman should be able to see all PGA components which require visual aid for connecti

and/or adjustment, particularly downward to a point on the front torso center-line six (6) inches below the neck ring. With the crewman standing and nodding in an erect PGA, he should be able to see the toes of his boots. The vertical field of vision of a crewman in a pressurized PGA and secured to the CM couch must not be reduced by fault of the helmet, upward or downward, when the crewman is subjected to a sustained acceleration of $+10G_x$, eyeballs in. Unrestricted range of vision should be as follows:

Horizontal Plane: 120° left, 120° right

Vertical Plane: 105° down, 90° up

With the head moved forward, eye relief for the primary pressure retention visor should be 2.06 inches. This eye relief must apply over a vertical range from 45° up to 10° down.

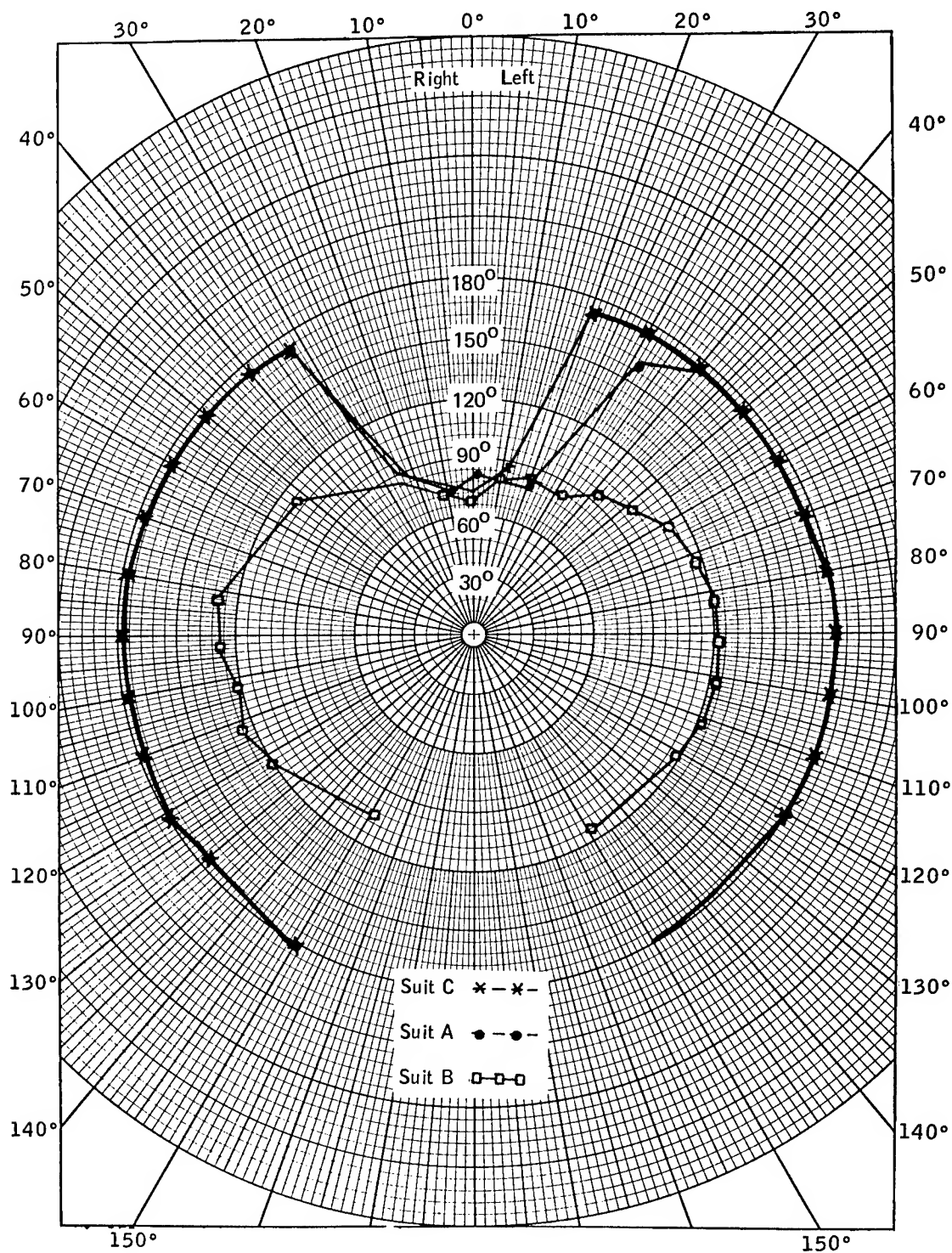
Table 16-24 covers the visual field capability of several prototype Apollo suits (185). In positioning the subject and the helmet in relation to the optical perimeter, the test helmet was rotated on the neck ring to align the helmet center mark with the neck ring center mark; the subject's head was then positioned inside the helmet to align the longitudinal center line of the head with the helmet and center marks of the neck ring. The complete system (head and helmet) was then positioned with the center of the subject's eye pupil normal to both the 90° and the 0° positions on the optical perimeter; and the helmet neck ring angle with the horizontal, positioned according to manufacturer's specifications. After completing this zeroing procedure, the helmet was secured in this zero position. During the test, the subject was allowed complete freedom of movement in the helmet, since the objective of the test was to ascertain the visual-field capabilities of each helmet as opposed to the subject's visual-field capabilities. Subsequent to the test, the subject was instructed to indicate the point at which he could no longer see the target as it was moved on the perimeter arm of 29 inch radius from directly in front (0°) to directly behind (180°). This procedure was followed for each angular increment of the perimeter arm, with four readings taken at each increment. The target was a disc one cm in diameter. Two additional measures were used to determine the downward and upward "operational" visual capabilities of each suit. These measures were taken with the subject standing and zeroed under the perimeter. To determine upward visual capabilities, the subject was instructed to follow the target on the perimeter arm as it was moved directly over him (the subject was allowed to bend his torso). To determine downward visual capabilities, the same test configuration was used; that is, the subject was standing and zeroed under the perimeter, but was allowed to bend his torso. The subject was instructed to indicate the highest point on his suit that he could see. A line from this point on the suit through the center of the eye pupil to the perimeter arm was then constructed to determine the downward visual angle measured from the horizontal. All of the above measures were taken under two conditions, pressurized (3.7 psig) and vented. To control test-subject variability, the same test subject was used throughout the visual-field test.

The mean value of the four trials for each angular increment of the perimeter was computed and plotted as shown in Figures 16-24 a and b. Table 16-24c shows the restriction under the "operational test and percent of specifications (see above and p 2-79 in Light No. 2). Upward visual-field restrictions

Figure 16-24

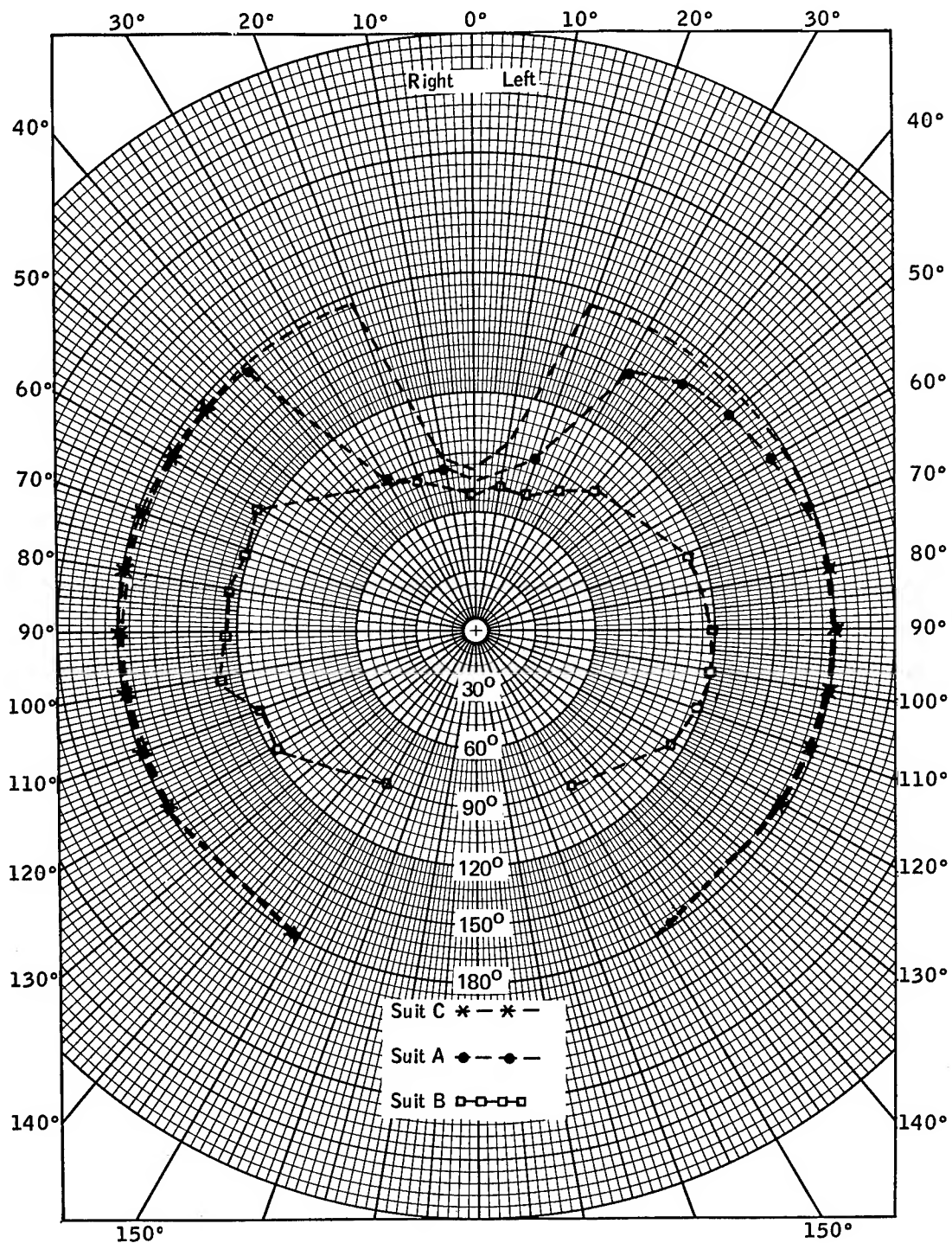
Dynamic Visual Fields within Soft-Suit Helmets

(After Jones⁽¹⁸⁵⁾)



a. Visual-Field Capability of 3 Prototype Soft Suits, Pressurized Condition
(Torso bending not allowed - See text)

Figure 16-24 (continued)



b. Visual-Field Capability of 3 Prototype Soft Suits, Vented Condition
 (Torso bending not allowed - See text)

Figure 16-24 (continued)

c. Suit Visual Capabilities - Up, Down, and Lateral Under "Operational" Conditions
(Torso bending allowed)

	Suit B, visual angle, degrees	Percent of specification (a)	Suit C, visual angle, degrees	Percent of specification (a)	Suit A, visual angle, degrees	Percent of specification (a)
Vented, UP, ^b	120	133	118	131	140	155
3.7 psig	110	122	115	127	105	116
Vented, DOWN, ^b	96	91	95	90	97	92
3.7 psig	91	87	95	90	95	90
Vented, LATERAL,	245.8	102	360	150	355	148
3.7 psig	249.1	104	360	150	355	148

^aSpecification: Up 90°; Down 105°; Lateral 240°.^bOperational measurements. (See text for details.)

in both suit A and suit C are intensified because the helmet of each suit is positioned in front of the suit longitudinal center line. This position limits the upward visual capabilities because ventrodorsal (backward) movement of the subject's head is restricted in each helmet. This helmet configuration also increases the eye-heart angle of both suit A and suit C. Suit A is superior in downward and upward visual capabilities, when the pressurized and vented conditions are considered as a single unit of interest rather than being considered separately. Operationally, this is a valid conclusion. It should be noted, however, that insofar as operational downward vision is concerned, each suit possesses the capability for the subject to see his respective gas connectors. Left visual-field restrictions for the suit A helmet are due to asymmetry of the helmet exterior painting rather than to any structural defect. It was recommended that the helmet of suit A be repositioned to a configuration more congruent with suit centering, thereby eliminating downward visual and eye-heart angle disadvantages. It was also recommended that the possibilities of a totally transparent helmet shell be explored to allow maximum visual field.

In the final rating, suit A rated first, suit C second, and suit B third. Under static and operational conditions, suit A provided evidence of superior visual-field capabilities. It should be pointed out that there was little difference between suit A and suit C, but there was a significant difference between these two suits and suit B which rated third.

CONFINEMENT, ISOLATION AND SENSORY DEPRIVATION

The confinement, social isolation and sensory deprivation factors are to be considered in space operations (99, 109, 236, 313, 326). The semantic problem may be dissected by the following classification (108):

<u>Confinement</u>	<u>Isolation</u>
a) <u>Physical</u>	a) <u>Social</u>
i) Restrictive	i) Solitude
ii) Determinative	A. Single
	B. Group
	ii) Rejection
	A. Single
	B. Group
	b) Sensory-Perceptual
	i) Sensory and perceptual reduction
	ii) Sensory and perceptual distortion

Confinement may be physical, temporal, or both. Physical confinement may be restrictive, in the form of physical restraint, or determinative in that the subject is free to move within his confines. Temporal confinement may be restrictive if the subject is forcibly limited in his activities for an imposed time, or determinative if he has to accomplish some achievement within an independently determined time. Social isolation involves isolation of individuals or small groups. It may be found in the presence of full sensory stimulation. Rarely, if ever, do confinement and isolation exist as single entities. Sensory or perceptual isolation, which involves essentially disturbances of perception, may arise from sensory reduction, or be associated with sensory distortion. It also may arise when stimuli do not provide adequate pattern information. Sensation may be present without perception. These are usually related to forced individual isolation.

It should be emphasized that there has been relatively little research in this general area. Much of the written material comprises reviews of a few basic experiments. The data in this section must be used with great caution.

Confinement

Confinement may be defined as a physical and temporal limitation on the activities and translational motions of an individual or group, occasioned by constraint, and sometimes associated with elements of perceptual and social isolation (11, 108, 230). The following section is taken directly from a recent review (108).

Along with many other modulating factors the response of the individual to confinement is primarily dependent upon the stress imposed by closeness of confinement, the extent of restriction, and the duration (11, 350). The initial response is one of general physiological activation, with an increased heart rate, respiratory rate, and blood pressure. Excretion of ketosteroids

and catecholamines tends to increase, while evidence of increased autonomic activation is given by a decrease in skin resistance, or increased skin conductance. These findings suggest a non-specific response to stress. Within about 3 to 7 days a new threshold is established and physiologic activity begins to recede to preconfinement level or below, although the pattern can be re-activated by emergencies. Continuation of the confinement, with reduced mobility and limited exercise, gives rise to signs of physical deconditioning, manifest particularly in the cardiovascular system, in musculoskeletal deconditioning, in fluid balance, and in hemopoietic system (45). These mimic the response to weightlessness (108). (See also zero gravity environment in Acceleration (No. 7)).

In a well-motivated, trained individual, if habitability is close to acceptable, there may well be no overt psychological effects; and even a covert response, as judged by interview, diaries, and measurement techniques, may be negligible (108). The occurrence of aberrant subjective and behavioral reactions, in particular, is to a considerable extent influenced by training, motivation, and experience. When manifest, they may occur in the form of overt or covert resentment, hostility, and frustration, directed in the case of the single confinee, at the environment itself, or at the unseen investigators or remote controllers (11, 108, 137, 158, 325, 361). Among multiple confinees, it is apparent that maintenance of good interpersonal relations can be considered of major significance. Among two-man crews in close proximity, considerable irritation can develop from the repetition of seemingly innocuous habits, inadequacies of personal hygiene, or divisions of labor, while three-man groups may be even more unstable, since any two can unite against the third. With multi-man groups the formation of cliques can become a real possibility. Personal space factors are important correlates of social emotional states for humans as well as for other animals (51, 207). Territoriality needs are known to be important to a very wide phylogenetic range of animal forms, including man. In the confined group, territoriality preferences may be difficult to satisfy (158). It has, nevertheless, been clearly and repeatedly shown that with careful selection, common motivation and wise leadership, crews can unite to minimize difficulty and ensure the success of a mission, although covert hostilities may be revealed later (289). However, details of this situation and training are still research questions.

Physical discomfort in terrestrial conditions can be severe. The discomfort, however, is more a function of immobility than confinement, as has been demonstrated in conditions where the same free volume per man is available, but in the one case the subjects are restricted, and in the other they have space-sharing mobility. Furthermore, since the discomfort is largely associated with the development of pressure points from the gravitational vector, it has not been a major feature of actual space operation.

The occurrence of perceptual aberrations, in the form of illusions and hallucinations, has been widely disseminated in the anecdotal and experimental literature. It is apparent, however, that this phenomenon is primarily associated with isolation and not with confinement (308). In fact where two individuals are simultaneously confined it is rarely recorded, and never with three or more. The occurrence of perceptual aberrations is, in fact, a feature of reduced or distorted sensory input, and does not take place in the presence

of good consensual validation. Numerous studies have been undertaken to examine such capacities as constructive thinking capability, memory, problem solving, performance skills, etc. under conditions of confinement (108). It is characteristic of the findings that while impairment may occur under conditions of isolation and reduced sensory input, there is little or no interference with intellectual function and performance capacity in confinement, per se, unless the demands of the tasks are inappropriate, or unless the confinement is extreme, or is accompanied by very adverse environmental conditions of heat, humidity, noise, etc.

Sixty studies of confinement under terrestrial and space conditions have been compared in Table 16-25a and the relation of symptoms to the volume and duration, plotted in Figure 16-25b. Classification is on a three point scale according to the amount of impairment observed, namely: no impairment (grade 1), detectable impairment (grade 2), and marked impairment (grade 3). Marked impairment was considered to be manifest psychophysiological change which might prejudice the safety or successful outcome of a mission. Detectable impairment was considered to be present in a situation which was tolerable, but was accompanied by measurable evidence of disturbance which could reduce proficiency. The classification of no impairment included those situations where some disturbance of homeostasis or comfort might have existed without loss of proficiency. It is considered that a classification scheme of this nature even though it makes use of widely different criteria for volumes and responses and is of a subjective nature, provides distinctions sufficiently obvious as to permit unobjectionable grading (108).

Three impairment zones can be defined in terms of duration and volume as indicated by the broad demarcation lines. The upper line defines a threshold of minimum volume per man which will be acceptable in most circumstances, even when modifying factors are not optimum. The lower line defines a threshold which will be unacceptable in most circumstances even if modifying factors are optimum. Between lies a zone where acceptability depends to some degree on optimum habitability, and personal factors. Extrapolation of the two lines suggests a junction at about 60 days at a volume which may represent the minimum acceptable for prolonged durations. The further direction of the curves is not known at this time, but it is interesting to note that Soviet work suggests that there is a resurgence of stress phenomena at about 60 days, in which case the threshold curve may again rise (108, 202). It is considered that the impairment which was demonstrated in the "Hope" studies resulted from the rigors of demanding work schedules, and not from confinement per se (5, 6). The marked impairment in the 152 days of confinement in the University of Maryland study is believed to be due to the nature of the programmed environment, publicity etc., and not to the confinement which, in fact, was minimal (97). The third and most significant exception is found in the Gemini series of flights. Since these were successful, the impairment cannot be classified as a grade three. Nevertheless, despite enthusiastic reports, considerable impairment did exist, particularly in the Gemini VII mission, as manifested by post-flight testing. In fact, it is probable that only the dedicated motivation and discipline of the crews, along with the added benefits of space sharing, made the missions as successful as they were.

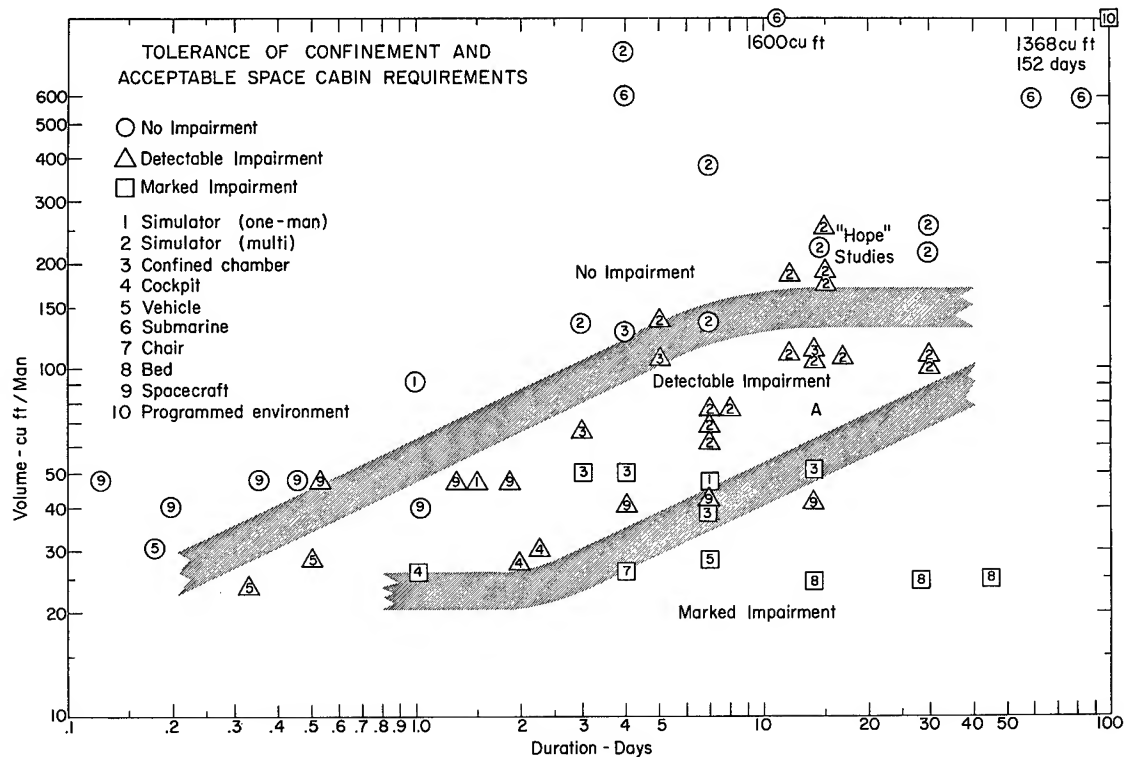
Key factors altering the curve are motivation, discipline, and experience. The habitability of the confined chamber both with respect to environmental

a. Extent of Impairment Resulting from Confinement (See text for details)

(After Fraser⁽¹⁰⁷⁾),

Table 16-25 (continued)

b. Free Volume-Duration Tolerance Factors in Confinement



a. Summary of experimental data.

(After Fraser⁽¹⁰⁸⁾)

c. Threshold Volume Requirements According to Duration of Mission

Duration (days)	Threshold of acceptable volume - Cubic Feet	Threshold of unacceptable volume - Cubic Feet
1	50	25
2	75	25
3	90	25
4	105	30
5	115	35
6	120	35
7	125	40
10	135	50
20	140	70
30	150	85
>60	? 150	? 150

(After Fraser⁽¹⁰⁹⁾)

factors such as atmospheric pressure and composition, heat, humidity, and noise, and with respect to hygiene, dietetic, recreational, and work facilities, is another factor. The nature of the actual activities and tasks demanded is also a significant factor, particularly the meaningfulness, and the degree of complexity. The requirement for realism and/or relevance in simulated tasks is also significant, in order to prevent disinterest. Knowledge of the expected duration of confinement is still another factor which affects tolerance not only subjectively, but objectively, in that a characteristic rise in morale and activity can be shown to occur at the midpoint of a known period, and again a day or so before the end. A most significant factor concerns physical fitness and exercise. There is no doubt that in terrestrial confinement, adequate exercise and mobility not only prevent deconditioning, but improve morale, and may even be associated with improved task performance. How much is adequate, however, is not clear and furthermore it must be remembered that weightlessness and immobility may well be synergistic in their causative relation to physical deconditioning. A final modifying factor relates to the number of confinees. As already noted, an increase in the number of confinees reduces some and creates other problems. At the same time it allows the possibilities of space-sharing, which effectively increases the available free-volume per men.

Disregarding cultural and other variables which may alter these thresholds Figure 16-25b indicates that for durations of 7 to 30 days, for small group crews, about 125-150 cubic feet per man of free space would be the minimum acceptable volume (134 - 138). Acceptability could be still further improved by promoting optimum habitability and working conditions (see below). Marked impairment would be expected with a free volume per man of less than 40 cubic feet for 7 days, or less than 85 cubic feet per man for 30 days.

For missions of months and years duration the critical volume factor is not as clear (109). (See Figure 16-26). An additive model of crew space for long duration missions includes the following (36):

$$\begin{aligned}
 \text{Volume} = & \text{(Seated volume per man + work volume per man +} \\
 & \text{ingress volume per man) x (Number of men)} \\
 & + \text{ Transfer volume per station} \\
 & + \text{ Intercompartmental transfer volume} \\
 & + \text{ Rest volume per crew off duty} \\
 & + \text{ Sustenance volume per crew} \\
 & + \text{ Logistics work space or equipment station} \\
 & + \text{ Equipment and storage volume for sustenance} \\
 & + \text{ Volume for waste}
 \end{aligned}$$

From anthropometric and other data, adequacy was defined as a minimum volume of 50 cubic feet per man (multiman) for 2 days, 260 cubic feet per man for one or two months, and 600 cubic feet per man for many months in Figure 16-26, Reference (36). Another approach using these criteria with an

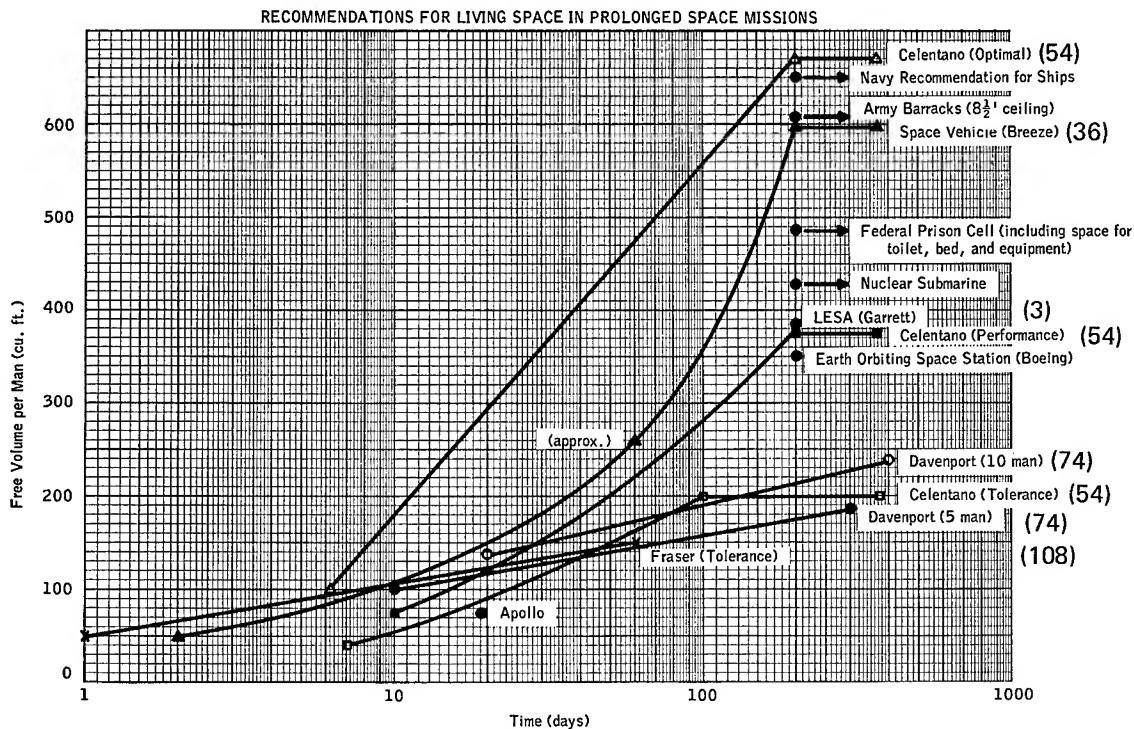


Figure 16-26

Recommendations for Living Space in Prolonged Space Missions
(After Fraser (109)) (See text)

adjustment for the debatable fact that an increased volume per man becomes necessary with increase in the number of crew, is also presented for 5 and 10 man crews in Figure 16-26, Reference (74).

Others have argued and shown in simulator studies that the occupants of a cabin allowing a large area, and other habitable features, would show little if any physiological differences from those in a normal life situation with a relatively sedentary occupation, such as that of an office worker (54). This study resulted in the curve of tolerability, the curves of acceptable performance, and the curve of optimal habitability shown in Figure 16-26. While the tolerance curve falls in line with other suggestions (74, 109), and may well represent minimal acceptability, there is some doubt as to whether the other two curves actually demarcate volumes for adequate and optimal habitability with the degree of accuracy implied. At the same time, the fact that free volumes found in certain operational situations, such as Army barrack allowances, Federal Prison allowances, and nuclear submarine allotments, lie within that range, suggests that the curves (54) are reasonable approximations. The data for Army barracks, prison, and nuclear submarines (11) are shown at the 200 day level for convenience. The arrows alongside indicate that the volumes designated may be occupied for longer periods.

Some other recommended volumes are also found to lie in the range suggested by Figure 16-26 (3, 235). On the basis of requirements for Arctic expeditions, a free volume of as much as 2000 cubic feet per man has been suggested for multiman operations (57). A volume of this size appears

unnecessarily large and luxurious for space vehicle conditions.

Although the volume requirements per man cannot be specified with any degree of authority, it would seem that for durations of 300-400 days, or perhaps beyond, the absolute minimal acceptable volume for multiman operations would be in the region of 200-250 cubic feet per man; the acceptable would be about 350-400 cubic feet; and the optimal, about 600-700 cubic feet, utilizing the volume for all purposes related to living conditions. To maximize habitability for long-duration missions, it has been suggested that design requirements should be based on the optimal level of 600-700 cubic feet per man (109

The mode of utilization and configuration of available space can be examined from different points of view, but several ground rules can be assumed. Thus, space must be provided for conduct of tasks relating to the mission, to vehicle management, and psychophysiological support. Space is also required for rest and off-duty time, for dining and food management, and for hygienic provisions. Under some circumstances, minimum hygienic facilities can be tolerated for long periods of time (296). Therefore, it is convenient to think of configuration in terms of functional units relating to these activities, although it should be realized that functional units are not necessarily topographical units. In other words, the volume allocated to one unit need not necessarily be located in one region of a vehicle. Except by invoking tradition, custom, and usage, it is difficult to justify logically the need for separating available volume into distinct regions, nor is it easy to determine how many such regions there should be. There is no doubt that highly motivated individuals, such as astronauts, can work, eat, rest, and sleep for days without leaving their seats, and still maintain acceptable performance. At the same time, various studies of habitable conditions (92, 109, 144, 368) have emphasized the need for variety, change, relief of monotony, and perhaps most of all, the desire to protect some modicum of voluntary privacy and storage of personal possessions.

It has been suggested that four functional units might therefore be delineated, namely:

Work unit: for the conduct of operational tasks, vehicle management, and psychophysiological support.

Public unit: for use in dining, food management, communal recreation, leisure, and exercise.

Personal unit: for sleeping, personal privacy, and personal storage.

Service unit: for toilet purposes, laundry, and public storage.

Several studies of the partition of this space for long duration mission have suggested the relative volumes of available space which might be occupied by each functional unit as follows (3, 74, 109):

Work unit:	40%
Public unit:	25%
Personal unit:	20%
Service unit:	15%

It is emphasized that these suggested proportions are approximate and tentative and represent merely a relative breakdown of available volume under what might be considered optimal conditions. In each case the actual proportions would be influenced by the requirements of the mission and the capacities of the vehicle and dwelling, and would need to be determined empirically by analysis of the requirements and the use of models and mock-ups.

Social Isolation (158)

Social isolation represents a separate source of potential difficulty in confined environments (6, 7, 8, 11, 34, 44, 49, 109, 135, 137, 155, 156, 157, 159, 160, 168, 240, 357, 360, 368). Confinement, however, is not a necessary component of social isolation (134, 305). Man is a social animal, highly dependent on other men in a variety of ways. The human personality typically includes a variety of social needs such as dominance and affiliation that can only be satisfied in interaction with other people. In a small isolated group, these needs are more likely to be frustrated than in a normal social situation where a wider variety of other people can be found (134, 135, 138, 158, 159, 361,). The small, isolated group also provides its members with fewer opportunities to make social comparisons, a process thought to be important in the development and maintenance of stable, accurate self evaluations. Men use social comparisons for testing the validity of their own performance, and the appropriateness of their own emotional reactions (15, 182). Both social need satisfactions and opportunities for social reality testing can be severely impaired in a small, isolated group. This can result in a heightened sense of frustration, decreased accuracy and stability of self concepts, and development inappropriate, invalid group norms that may be at variance with or irrelevant to the group's initial primary mission.

Another aspect of being confined with a relatively few other people is the degree to which it accelerates the social acquaintance or social penetration process. Anecdotal reports suggest that certain people in such situations use each other as significant sources of stimuli to a greater degree than is normal, and get to know the intimate details of each other's lives very thoroughly. The rate at which intimate information about each other is acquired, however, may exceed the rate at which individuals can learn to accept individual idiosyncracies or markedly different value systems (158). The theory of social balance holds that tensions are created between individuals when they have different attitudes or oral opinions about a third person, object, or set of objects. The more central these attitudes and opinions are to the personalities involved, the greater amount of tension social imbalance will create. In the normal course of social existence, men avoid intimate contact with others whose value systems are markedly different. In the confined group, such avoidance may be impossible.

The accumulation and escalation of interpersonal tensions generated by lack of social need-satisfactions and social imbalance makes interpersonal conflict in confined groups a more difficult problem to manage than it normally would be. Lack of privacy, inability to establish and maintain territorial ownership, inability to find convenient scapegoats outside the group for displaced aggression, and restricted opportunities for releasing tension through

muscular activity all may contribute to evermounting interpersonal hostility. Pairs of men hypothetically incompatible with regard to people showed a high degree of territoriality behavior, whereas incompatibility with regard to non-people-oriented considerations, such as dogmatism and need achievement, did not particularly produce territoriality (318). Incompatibility with regard to egocentric frames of reference, such as dominance needs and dogmatism, produced a high rate of "together activity"--largely argumentative in nature--while incompatibility on sociocentric frames of reference such as needs for affiliation and achievement generated a tendency towards social withdrawal--more alone than together activity.

Even though reporting higher levels of subjective stress, isolated pairs of subjects tend to perform better on group task than do unconfined controls (158). This appears to be due to the performance enhancement value of moderate levels of stress in isolation (96). A high rate of test mission aborts, can be generated by simply reducing the variety of tasks required of subjects and increasing their expectations regarding duration of confinement from unspecified to time-limited exposures (158). The stresses of stimulus reduction, isolation, and confinement can be considerably relieved by stimulus enrichment procedures, increased communication with the outside world, and careful attention to group composition considerations (158, 159). It is clear from anecdotal literature that small groups of men can survive four months of social isolation and confinement. Longer periods of time are considerably more doubtful. More thought and research needs to be given to these aspects of man in a closed system for prolonged periods of time (182, 304). Model building and computer simulation of the problems is continuing (119, 273). Selection of group members and leadership criteria are also under study (134, 135, 138, 139, 219, 255, 264, 284, 285, 286, 287, 288, 289, 322).

Sensory and Perceptual Deprivation

Exposure to this condition may be expected in space operations most often when other members of a crew are dead or lost and the lone survivor is cut off from communication with earth. However, monotonous confinement of groups can result in problems in this sphere. Stimulus reduction or comparative monotony is not necessarily associated with confinement (301). It is now generally recognized that man needs a minimum level of stimulus variety below which somewhat bizarre, maladaptive behavior and subjective experiences are reported (13, 44, 67, 110, 158, 167, 191, 196, 203, 210, 228, 250, 308, 316, 348, 349, 375, 377, 378, 380). These may include a tendency to withdraw into ones self, intense fears of losing ones rationality, hallucinatory behavior, decrements in certain perceptual and cognitive functions, increased need for stimulus inputs of almost any nature, and changes in sensory acuity, generally in the direction of heightened tactile and auditory sensitivity. Darkness or monotonous, diffuse light patterns of low intensity predispose to the hallucinating behavior (110). Marked reduction in frequency of EEG alpha-rhythms have been seen as possibly indicative of a central nervous system change (312, 348, 349, 376, 379). Significantly, the EEG does not return to normal for several days following a two week period of sensory deprivation. These results have been reported from studies of sensory and/or perceptual deprivation, but such data as are available suggest that similar phenomena perhaps to a less intense degree occur in group confinement situations involv-

ing a relatively monotonous existence even though not stimulus-deprived in the traditional sense (158, 174, 301). Internal time consciousness is altered by such conditions (101, 220, 314), but exposure of more than 3 hours is probably required (283).

A great deal of attention should be given to developing a habitable living arrangement, in particular with private areas affording relief from constant interaction with other crew members (108, 109) (see also page 16-76). Provisions should be made for both active and passive types of recreation (109). It is also important that optimum amounts of communication with Earth be provided, to minimize the sense of isolation, but avoid excessive communication. One must avoid aggravating conflicts which often arise from interaction between isolated group and "external controllers" (325).

The possibility of giving the men experience in the situation of confinement, social isolation and sensory deprivation for training purposes should be mandatory (255). If handled properly, this would give the men a chance to experience some of the frustrations inherent in these situations, some of the behaviors that may appear in themselves and others, and to practice ways of handling them. Such experiences, perhaps repeated several times, with an opportunity for discussions intervening, could provide the means for effectively handling such occurrences as they arise during the mission itself. Giving the astronauts such experiences is in accordance with the current philosophy of their training program, in that emphasis has been placed upon their experiencing, in as great a degree of realism as possible, all anticipated situations of space flight prior to their undertaking the mission itself. Experience with detailed simulation of a lunar mission is available (124, 125, 126, 127). These may be used as models of operational study of crew interaction and efficiency. However, a problem arises regarding how much simulation would be required for longer missions of many months (109). A compromise that seems attractive would be to prepare a series of films showing groups of men in laboratory situations of confinement, demonstrating examples of boredom, aggression and conflict, both overt and covert, and the methods, good and bad, used by the personnel to deal with these events (100). This could then constitute a basis for round-table discussions by the astronauts, along the lines of evaluating how likely it would be that such situations would arise in space flight, how effectively the situations were dealt with by the personnel in the films, and what methods might be more effective in space flight.

A general review of problem areas in the handling of confinement, social isolation and sensory deprivation is available (369). A review of Soviet studies in this area has been published (196).

WORK-REST-SLEEP CYCLES (WRS)

Man is influenced by the diurnal periodicity of the physical world surrounding him. His typical work-rest-sleep cycle (WRS) is thus based on a 24-hour rhythm (16, 17, 20, 260, 307, 326). His physiological function and, as a result, his psychological performance vary according to this rhythm. As a result, any alteration in the WRS to which the man is adapted will cause

variations in physiological functions and psychological performance (6).

Diurnal or Circadian Rhythms

Figure 16-27 is an example of some of the diurnal or circadian rhythms. At least 50 are known (19). The variations in function are the result of discrepancies in phase relationships between man's endogenous metabolic clock, according to which many physiologic functions are moderated with regular periodicity, and the external environment (65, 141, 260, 278, 280, 298, 307, 326, 353, 354, 355, 356). The biological functions, the most easily measured of which are pulse rate and body temperature, become "entrained to" or synchronized with this schedule. These functions follow a rather consistent course with a daily high point sometime during the early evening hours (between 1600 and 2000) and a low during the early morning hours (between 0400 and 1000). This cycling occurs whether the man is awake or

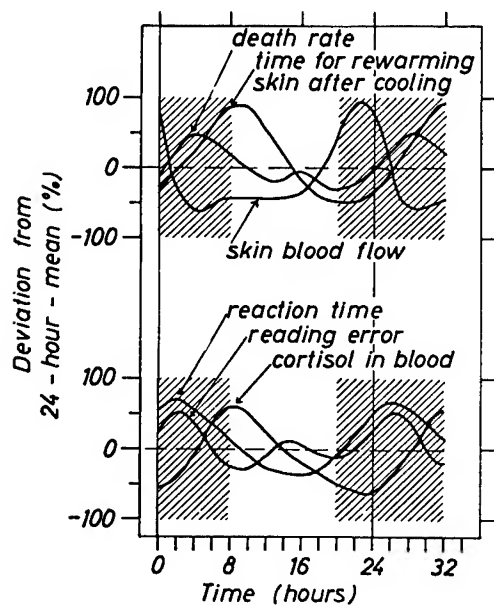


Figure 16-27

Schematically Drawn Curves, Indicating the Approximate Phase and Range for 6 Circadian Functions in Man.

(From several publications of text)

Dashed area represents dark-time.

(After Aschoff (19))

asleep. A further relevant point is that this curve is maintained for a period of four to six days after a marked change in the day/night relationship (153 154). It is also relevant that this curve is generally maintained by individuals working night shifts. This presumably results from social factors governing the man's off-duty activities. When the endogenous metabolic clock is out of phase with the external environment (e. g. , when one remains awake from 2200 to 0800, a time when one is usually accustomed to sleeping), human performance decreases and a man is said to be in a state of asynchrony (153 154, 314). In this state, hunger and somnolence or insomnia will be present at the "wrong" times. This can be demonstrated by taking various physiological measurements during asynchrony (body temperature (193), endocrine and salt excretion patterns in urine (24, 117, 141), heart rate (193), EEG (103), and gastrointestinal motility (193)) and comparing them with those obtained on the same individual when in synchrony with his external environment. There is a suggestion that physical immobilization reduces the intensity of the usual physiological cycles (251).

Studies of phase shift in free-running cycles without time cues are now under way (16, 37, 280). These are of vital importance to WRS programming. When men are kept isolated in a constant light, temperature, and sound environment where no time cues are available, their endogenous rhythms begin to override the previously entrained functions. There is a continuous delay in the time of getting up as well as in the time of urine calcium and potassium excretion and body temperature rise. The average period for all functions is 25.1 hours. The urine volume, calcium and potassium have a 26.1 hour cycle. Little is known of the mechanisms of these internal, oscillating control systems (16). Cyclic change in light intensity entrains the rhythm more than does temperature cycle (19). Alteration of the key cuing mechanism or "Zeitgeber" can desynchronize the different physiological cycles from one another. Personalities and activity habits of isolated individuals interact to modulate physiological and performance responses to environments free of time cues (280). Theoretical studies suggest that organisms with a natural period which is relatively short as compared to the time-cue cycle become entrained with a leading phase, the amount of phase angle difference depending on the ratio of the two natural frequencies (18, 19, 353). The longer the natural period, the more it lags in phase behind the time cue during entrainment. It is possible to train animals and man to an artificial time cue which is a multiple of 1:3 to the natural cue. This suggests that scheduling of the WRS cycle should be so devised as to have the time cue cycle a submultiple of 24 hours. Evidence that this is so will be discussed below (2, 6).

The problem created by scheduling WRS cycles for long aerospace mission is complicated by the cumulative effects of prolonged alteration in W, R, and S on performance (79, 267). It is compounded by the possibility that an emergency may require continuous performance of alertness at high levels for unknown lengths of time. Most of the present knowledge about work-rest-sleep cycles comes from ground-based studies obtained over periods of less than 24 hours. Small numbers of subjects, variability of motivation, and diversified backgrounds make generalization from the literature difficult. Both temporal and non-temporal factors affect work, rest, and sleep. The temporal components are summarized in Figure 16-28.

Major emphasis in the literature has been placed on the durations of the work (dw) and sleep (ds) periods, moderate emphasis on the total "daily" periodicity (DT), and very little on the ratios of work to rest (dw/dr) and sleep to wakefulness (ds/daw).

Sleep Duration

Satisfactory psychological performance is dependent upon an adequate sleep-wakefulness cycle, but few studies have been done to determine the optimum number of hours of sleep required per hours of waking time, i. e., ds/daw. The usual study has investigated the ratios, ds/DT, (DT = 24 hours) to determine the amount of sleep spontaneously taken per day without regard to performance. It has not been demonstrated at this point whether man needs 6-8 hours of sleep in every 24 or if, up to a limit, man can take any number of hours of wakefulness as long as they are offset by hours spent sleeping in the ratio ds/daw = 1/2-3. On the short side, the quality of afternoon performance improves almost linearly as sleep duration is increased from one to six

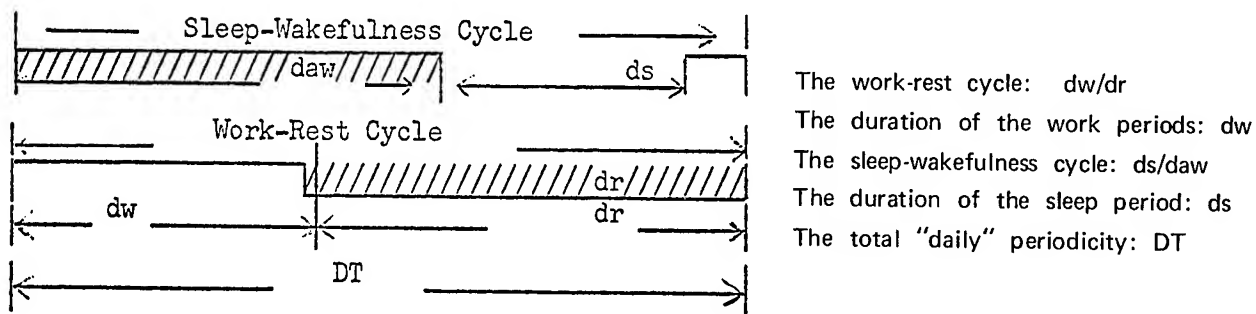


Figure 16-28

Man's Daily Activities Categorized to Form a Sleep-Wakefulness Cycle and a Work-Rest Cycle. (The two cycles are not habitually in phase with each other.)

(After Deutsch⁽⁷⁹⁾, adapted from Kleitman⁽¹⁹³⁾)

hours (338). Beyond a duration of six hours of sleep, improvement is less marked and is completely absent when sleep is lengthened from 8 to 10 hours in every 24.

One could infer that the ds/daw ratio for optimum performance is $1/2-3$. This is consistent with the results of Table 16-30 in which a ration $ds/daw = 1/3$ was found adequate (1).

It is known that some finite amount of sleep is required to preserve the physiological balance between waste and repair. The exact amount needed can be expected to vary with the individual's metabolic state and the type of work being done. Relatively large variations in needs have been demonstrated in the literature (142, 193, 195, 249, 327, 370). Statistical evaluation of ds ($DT = 24$ hours), as observed in large numbers of normal volunteers, points to a mean value of 7.5-8 hours required per 24 (66, 193, 194). S's in one study stated they "felt better" after an 8-hour sleep period than after 6 (327). Performance measures did not bear out this difference in "feeling," however, as the S's with 6 hours sleep performed equally as well as those with 8. Although there may be no physiological need for the extra two hours sleep as far as performance is concerned, it still has a beneficial effect upon the subjective feelings of the subjects and is, therefore, probably desirable.

Under normal conditions, a man goes to bed when he is tired and ready for sleep, and, generally, he has difficulty falling asleep at other times, presumably because of the influence of the "activation period" of his previously entrained cycle. This problem comes into focus when there has been a drastic alteration in the sleep/wakefulness schedule in relation to the activation curve. The individual has difficulty getting to sleep even when he has been awake for well beyond his normal span of wakefulness. Even though the activation curve may continue its normal course, there is an apparent psychological adaptation after about four days on a new schedule. This underscores the desirability of preadaptation to a given schedule if that schedule is to differ significantly from the normal regime of 16 hours of wakefulness and 8 hours of rest (62).

Weightlessness will undoubtedly have some effect on the ds required.

Speculation has it that less sleep will probably be required since the decreased metabolic energy needed to function in a weightless field may decrease the need for sleep, thus creating additional waking hours (314). Experimental attempts, however, to simulate weightlessness using water immersion techniques have led to conflicting results. A ratio of $ds/DT = 2/24$ was found to be the maximum required during one seven-day study (122). Other subjects immersed 10 hours out of 24 noted no alteration in their pre-test ds/DT ratio of $8/24$ (123).

The following have been the experiences in orbital flight (27). Astronaut Gordon Cooper--22 orbits, 34 hr., 20 min., 1963--found that even early in flight, when he had no tasks to perform and the spacecraft was oriented so that the earth was not in view from the window, he easily dozed off for brief naps. During the period designated for sleep he slept only in a series of naps lasting no more than one hour each. His total sleep time was about four and one-half hours. He stated that if there had been another person along to monitor the systems he could have slept for much longer periods. He further stated that he slept perhaps a little more soundly than on earth (53). The long period of alertness, of course, enabled Cooper to utilize his orbital time to the optimum for his operational and exploratory tasks.

In 1965 two more orbital flights by American astronauts were made, in which special attention was given to the sleep and wakefulness cycle (29). Difficulty in sleep programming was elucidated by the problems in this flight. The GT-4 and 5 crews (4 and 8-day missions) reported no difficulty in performance related to the 45 minute darkness and daylight cycle created by orbital flight. There were some definite sleep problems. A great deal of difficulty was encountered in obtaining satisfactory sleep periods on the 4-day mission. Even though the flight plan was modified during the mission in order to allow extra time for sleep, it was apparent, post-flight, that no long sleep period was obtained by either crewman. The longest consecutive sleep period appeared to be 4 hours, and the command pilot estimated that he did not get more than 7-1/2 to 8 hours good sleep in the entire 4 days. Factors contributing to this lack of sleep included: (1) the firing of the thrusters by the pilot who was awake; (2) the communications contacts, because the communications could not be completely turned off; and (3) the requirements of housekeeping and observing, which made it difficult to settle down to sleep. Also the responsibility felt by the crew tended to interfere with adequate sleep.

An attempt was made to remove a few of these variables on the 8-day mission and to program the sleep periods in conjunction with normal nighttime at Cape Kennedy. This required the command pilot to sleep from 6 p. m. until midnight, Eastern-Standard Time, and the pilot to sleep from midnight until 6 a. m., each getting a 2-hour nap during the day. This program did not work out well due to flight plan activities and the fact that the crew tended to retain the midnight to 6 a. m. - Cape Kennedy nighttime period. The 8-day crew also commented that the spacecraft was so quiet that any communication or noise, such as removing items attached with Velcro, aroused them.

On the 14-day flight, the flight plan was designed to allow the crew to sleep during hours which generally corresponded to nighttime at Cape Kennedy. There was a 10-hour period established for this sleep, and it worked out very

well with their normal schedule (Figure 16-29). In addition, both crewmen slept at the same time, thus eliminating unnecessary noise from the actions of the other crew member. The beginning of the scheduled rest and sleep period was altered to move it one-half hour earlier each night during the mission in order to allow the crew to be up and active throughout the series of passes across the southern United States. Neither crewman slept as soundly in orbit as he did on earth, and this inflight observation was confirmed in the post-flight debriefing. The pilot seemed to fall asleep more easily and could sleep more restfully than the command pilot. The command pilot felt that it was unnatural to sleep in a seated position, and he continued to awaken spontaneously during his sleep period and would monitor the cabin displays. He did become increasingly fatigued over a period of several days, then would sleep soundly and start his cycle of light, intermittent sleep to the point of fatigue all over again. This response may represent inability to sleep in a seat or natural reaction to responsibility. The cabin was kept quite comfortable during the sleep periods by the use of the Polaroid screen and some foil from the food packs on the windows. The noise of the pneumatic pressure cuff for Experiment M-1 did interfere with sleep on both the 8- and 14-day missions. The crew of the 4-day flight was markedly fatigued following the mission. The 8-day crew were less so, and the 14-day crew the least fatigued of all. The 14-day crew did feel there was some irritability and loss of patience during the last 2 days of the mission, but they continued to be alert and sharp in their responses, and no evidence of performance decrement was noted. (See electroencephalographic data below.)

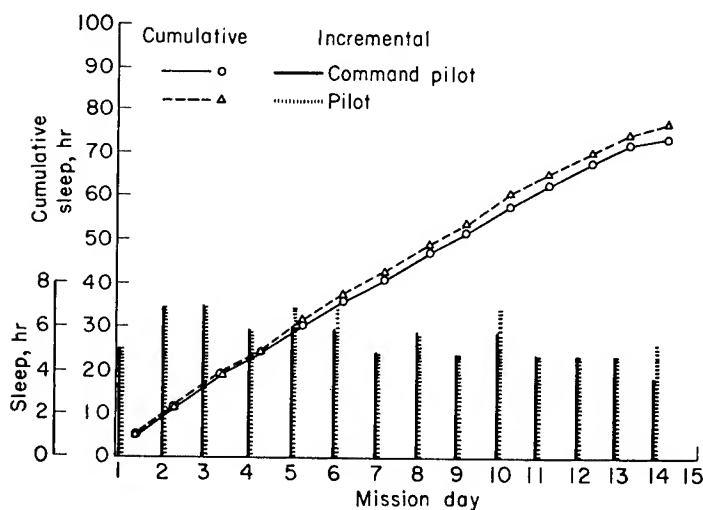


Figure 16-29

Sleep Data for Gemini VII Flight Crew
(After Berry et al⁽²⁹⁾)

Soviet experience with sleep in orbit is of interest. The sleep of Soviet cosmonaut, Gherman Titov - 17 orbits, 25 hr., 18 min., 1961--was not without interruptions (323). After seven orbits he felt a definite state of fatigue. When he flew over Moscow at 6:15 p. m., he prepared for sleep, according to schedule, by releasing special belts from the side of the pilot's seat. He strapped his body to the contour seat, and after adjusting the seat to the bed position, he promptly fell asleep, but awakened much earlier than scheduled. This happened during the eighth orbit. When he opened his eyes he saw his arms dangling weightlessly, and his hands floating in mid-air. "The sight was incredible," Titov reports. "I pulled my arms down and

folded them across my chest. Everything was fine--until I relaxed. My arms floated away from me again as quickly as the conscious pressure of my muscles relaxed and I passed into sleep. Two or three attempts at sleep in this manner proved fruitless. Finally I tucked my arms beneath a belt. In seconds I was again sound asleep." Titov further states: "Once you have your arms and legs arranged properly, space sleep is fine. There is no need to turn over from time to time as a man normally does in his own bed. Because of the condition of weightlessness there is no pressure on the body; nothing goes numb. It is marvelous; the body is astoundingly light and buoyant...I slept like a baby." He awoke at 2:37 a. m., Moscow time, and was a full 30 minutes behind schedule because of oversleeping. He immediately started the required "morning calisthenics." Thereafter he carried out all scheduled assignments. Only his motion sickness interfered with normal performance. It is of interest to note that Titov's sleeping period coincided largely with nighttime over Russia. This also was true of the other Russian cosmonauts, and may have been so planned.

Valery Bykovsky - 81 orbits, 119 hr., 1963--slept four times for periods of eight hours, alternating with periods of sixteen hours of wakefulness (252). During this flight and that of Valentina Tereshkova - 47 orbits, 71 hr., 1963--"the diurnal periodicity of physiological functions changed only during the first and last days of the weightless state, which was most probably associated with the emotional strain." During the phases of wakefulness, brief rest periods were usually scheduled for times when the spaceship was not over Russia. "It should also be noted that at night, during sleep, nearly all cosmonauts displayed a greater reduction in pulse rate than that recorded during the same hours in earlier space simulated flight." (116).

The three-man team of the spaceship Voskhod - 16 orbits, 24 hr., 17 min., 1964 - rested and slept in shifts during their 24-hour flight.

The reported sleep and wakefulness time patterns in orbital space flight reflect, by and large, the physiological circadian cycle of 24 hours. For orbiting astronauts, the earth temporal zones are irrelevant to the sleep cycle. With regard to these zones they are--in a state of asynchrony. Their basic guiding time has been Greenwich time or Universal Time (U. T.). Nevertheless, for physiological and operational reasons it seems to be very desirable that their physiological clocks remain synchronized with the local time of the launch time zone, or in a broader sense, to the time zone range of the home country to which they were adapted during the prelaunch period (314). But in extended (geocentric and heliocentric) space flights, the astronauts probably will follow a physiological sleep and wakefulness cycle adjusted to their duties, and not necessarily completely corresponding to the temporal pattern of the physiological circadian cycle on earth. If operational necessity requires that the basic sleep-wakefulness cycle be of a non-24-hour periodicity, then an artificial cycle that is longer than 24 hours might be better than one that is shorter (37, 194, 195). This suggestion might be questioned, however, in view of the long and successful experience of the United States Navy in maintaining watch schedules based on work-rest and sleep-wakefulness cycles of 12-hour duration. However, since the 24-hour schedule is a multiple of 12, it may be that the 12-hour schedule is qualitatively more similar to the 24-hour schedule than is an 18-hour schedule. (see below)

On the moon, the physiological sleep and activity cycle will be completely independent of the physical or selenographic day-night cycle, which is 27 terrestrial days in length. In addition to sunshine, with an illuminance of 140,000 lux (lumens per square meter), the earthshine at full earth with an illuminance 75 times stronger than that of the moonshine on earth at full moon, provides a photic situation approaching a dim daylight situation on earth (314). Furthermore, there may be locations with no effective illumination at all (caverns), or places with constant sunlight as on the "mountains of eternal light" near the south pole. Be that as it may, the photic environment on the moon does not provide a "Zeitgeber" comparable to the 24-hour dark-light cycle on earth. Therefore, the astronauts might adopt a sleep and activity cycle of the terrestrial circadian pattern, modified by their special tasks and by the lower gravity on the moon.

On the planet Mars, the day-night cycle is only 37 minutes longer than that on earth (314). The sky is dark bluish in color, excepting regions covered with thin whitish clouds. Solar illuminance on the Martian surface at noon may reach one-third of that on earth. Thus, the temporal dark-light alternation on Mars offers time cues similar to those on earth.

Duration of the Work Periods (dw)

Studies of the work periods (dw) have been typically conducted using a total "daily" periodicity (DT) of 24 hours, and have measured performance as a function of the total duration of the work period in industrial settings. The primary factors to be considered in the selection of the length of the duty period relate to the nature of the activity required of the operator in the performance of his duties (62). Account must be taken of both the levels and varieties of the demands placed on him in carrying out his tasks. For example, some tasks involve only passive performance on the part of the operator in that several minutes may elapse during which no event to which he must respond will occur; this sort of task is exemplified in radar watchkeeping. At the other extreme are tasks that require active participation of the man by more or less continually taking actions of some sort, e. g., manual control of the vehicle on re-entry. An important psychological factor underlying this distinction is the effect that these two different kinds of tasks exert on the operator's level of alertness. Passive tasks produce or contribute to decreased alertness whereas, at least up to some level of workload, active tasks tend to sustain or increase alertness. The variety of tasks--again up to some level of workload--also tends to promote alertness. However, moderately high workloads on tasks that require the "simultaneous performance" of psychologically disparate functions (e. g., mental calculations and code solving) are quite vulnerable to losses in alertness, and this is especially true for task combinations in which timing is critical. Thus, in a sense, an alertness paradox is produced (62).

Many of the conditions under which performance decrements have been observed in laboratory studies are not at all likely to occur in properly human-engineered man-machine systems. Typical of this class of studies is the vigilance experiment. Here, the occurrence of decrements is largely dependent upon the presentation of a single task using infrequently occurring, near-threshold signals of uncertain nature to which the man must respond (303). With these conditions, decrements are exhibited over performance intervals

as short as 30 minutes. However, even with single tasks, when the signals have high attention value or are alternated or made redundant, performance can be maintained for much longer periods without apparent decrement (39 , 40, 128, 212). Electrophysiological (EEG, EOG, GSR and nuchal electrogram) correlates of vigilance are under study (28, 30, 225).

With tasks in which the operator has control over his rate of activity (as in industrial situations involving piece-work production), the man typically works at a near maximum rate for a period; he then takes either an official or unofficial rest break, after which he resumes his original rate. Thus the period of continuous work in most industrial jobs is typically about two hours is seldom longer than four hours.

The optimum length of duty period has not been investigated except within rather narrowly defined limits as regards the numbers and kinds of tasks the man is required to perform. Thus, even though the operational work situation and performance requirements can be specified exactly, substantive data relevant to the determination of the appropriate length of duty periods are in short supply. However, the data that do exist suggest that work periods on the order of four hours represent the duration of performance that should be expected as a matter of routine without encroaching on the maximum efficiency of which the operator is capable (Figure 16-30). When the level of performance necessary to satisfy the mission requirements is substantially below the operator's maximum capabilities, this figure can be increased. But, in determining how much it can be increased, importance attaches to the probability that an emergency might arise that would require maximum capabilities and to the speed with which the operator would have to be able to exercise those capabilities. Fortunately, except when his condition has reached a point of extreme deterioration, man can rather quickly rise to most any situation. The critical questions are, "How rapidly must he rise? how far? and for how long?" (62).

The Work-Rest Cycle

The ideal work-rest cycle would be one in which the total "daily" periodicity (DT) equaled 24 hours, distributed in a manner to which humans are already adapted. The 90 minute day-night cycle of orbital flight makes this ideal rather difficult to attain in the operational situation.

The most common division, used in the U. S. submarine fleet, is the 4-on and 8-off schedule of standing watch, which is operation on an artificial 12-hour cycle (193, 194). Reports in the literature would indicate that while the duties of a submariner may be satisfactorily carried out on such a schedule, efforts to establish a 12-hour physiologic rhythm in man have been uniformly unsuccessful on subjective, biochemical and hematological bases (142, 221, 222).

Experiments have been performed to discover what dw/dr ratios and durations yield the best performance. The results of this experimentation are summarized in Table 16-30. Unfortunately the durations are not very long. The consistency, however, within experiments and the consistency between recommendations is interesting. Both authors of earlier studies, (References 1 and 43), recommended a dw/dr ratio of 2/1 (hours:4/2) and indicate a general agreement of little or no performance decrement being

Table 16-30

Results of Experiments Relative to Performance During Various Work-Rest Cycles

Ratio dw/dr	Hours dw/dr	Comments	DT	Subjects #	Days N	Ref.
2/1*	4/2	"Wide variation in individual performance; subjects worked effectively."	6	11	15	1
2/1*	4/2	"Experiment too short" but "no difference in performance", data indicated trend toward better 4/2 performance if experiment had been prolonged."	6	12	4	1
3/1	6/2*		8	10	4	1
1/1	8/8	4/4 and 2/2 adjusted "better" than did 8/8 and 6/6.				1
1/1	6/6					1
1/1*	4/4					1
1/1	2/2	Maximum severity--not recommended for routine use.				1
2/1*	4/2*	No marked performance decrement; recommended over 6/2.	6		8	43
1/2	4/8	Confirms that it is difficult to establish a physiological 12-hour (DT)--See Ref. 90.	12			193
1/1	4/4		8	2	7	265
1/1	4/4		8			311
2/1	4/2	With proper selection and motivation this schedule can be attained with no degradation in performance.	6	6	15	6
1/1	4/4	Best schedule studied. Function appeared normal; physiological phase shift toward end of period noted.	8	10	30	6
2/1	4/2	Steady work period of 40 hours on day 6 and 7 poorly tolerated; performance is generally poorer than equivalent 4/4 schedule.	8	6	12	5
1/1	4/4	Steady work period of 44 hours on day 6 and 7 well tolerated; performance was good.	6	10	12	5

noted. In addition, the dw/dr = 2/1 ratio is recommended by both over the dw/dr = 3/1 ratio on a subjective and objective basis. One group feels that it is probably feasible to expect a highly motivated man to maintain acceptable performance levels on a 4/2 schedule for a period as long as 15 days, and, probably, 30 on the basis of some subjective statements. The results of other subjective studies indicated that some individuals adjust more favorably in groups where a 4-on and 4-off schedule was used (1, 61, 265, 311).

Recent laboratory studies have shown that most subjects can maintain satisfactory performance without decrements over a period of 30 days while following a 4-hours work, 4-hours rest schedule around the clock (5, 6). A modified control study was conducted using a 4-hours work, 4-hours rest, 4-hours work, 12-hours rest schedule. No limitations were placed on subjects

during the 12-hour rest period. The performance of this group of subjects over a period of 12 days was essentially the same as that of subjects working 12 hours per day while confined to a simulated crew compartment. On the assumption that a 30 day period was sufficient to reveal any adverse reactions, one can conclude from these results that the short (4-hour) sleep periods were sufficient to maintain the "psychological status" of the operators. These subjects, who were rated pilots, felt that they could have performed their normal flying duties on a 4/4 schedule throughout the period of the study and the majority thought they could have continued to do so indefinitely. Periods of sleeplessness during the 4/4 schedule were better tolerated than on a 4/2 schedule.

In the 30-day study with subjects following a 4-work/4-rest schedule, there was some evidence that the magnitude of the normal physiological periodicity was reduced toward the end of a month. Specifically, whereas for the first 25 days of the study the fluctuations were significant, during the 26th through the 30th days the cycling was not significant. In studies of submarine personnel it was found that crewmen on a 12-hour duty/rest cycle showed a double, body-temperature curve (193). These results suggest the possibility that the subjects in the 30-day study on a 4/4 schedule may have been tending toward a "triple" curve of physiological cycling. Further work is required on the mechanism behind these phase shifts. It may be that the 4/4 schedules do not present sufficient time cues. Not all of the physiological functions appeared to behave similarly. In only one of the groups did pulse rate really reach a new steady phase-angle difference. The cause of delay in phase angle shift is also not clear. An understanding of these phenomena will permit more valid extrapolation to missions of longer duration.

Human variation in ability to adapt to an atypical (non-24 hour) WRS cycle has ranged from one week to six years (37, 122, 193, 204, 267). Average times required seem to be in range of 2-3 weeks for complete adaptation (335). Reports of abrupt, rapid adaptation are more surprising than failures to adapt. All investigators seem to agree on the wide degree of variation in the rate and completeness of adaptation and the work out-put after adaptation (112). It is possible that only a five day adaptation period may be required for normal function (1, 261).

The ratio of mean temperature range (MR) to the range of the mean temperature (RM) has been used as a measure of adaptability (193). The degree of fit of observed temperature cycle to expected changes after being on new cycle 24 hours has also been used as a measure of adaptability.

The maintenance of a stable sleep-wakefulness cycle, as indicated by a superimposable body-temperature curve, peaking during wakefulness and dropping during sleep, serves a dual purpose. It promotes greater alertness and efficiency during working hours, and easier onset of sleep. The consistent, day-to-day adherence of a stable sleep-wakefulness cycle is, therefore, to be recommended.

Efficiency During Wakefulness

Efficiency during wakefulness is a major criterion. Efficiency of performance follows a 24-hour rhythm (193). It is low upon arising, shows an initial

ascent phase, a plateau in the middle of the day, and a terminal descent phase. Performance immediately upon getting up from a period of sleep is often poorer than it was just before retiring and is worse after deeper stages of sleep (148 , 149, 338). During split, sleep-wakefulness cycles (4 hours asleep, 4 hours awake, 4 hours asleep), a "very low" capacity for work through the middle four-hour waking period is seen (193). Similar findings were noted using a 3-hour sleep, 3-hour awake, 3-hour sleep schedule (173).

Over a long period of time these circadian periodicities in efficiency have direct implications on the performance levels to be expected of the operator. These implications are borne out in data obtained in laboratory confinement studies. The performance of the man on some tasks and task combinations reflects the same sort of periodicity that is found in the biological measures.

In the 30-day study with the 4/4 schedule referred to in Table 16-30, this cycling was present even though the low point of the performance curve always exceeded in efficiency the high point of comparable subjects following a more demanding schedule (6). In this regard, it should be noted that it may well be that the data obtained using a 4/4 schedule actually give an optimistic view of the criticality of the association between the biological and performance data (62). Specifically, since the duty periods never exceeded four hours, the potentially detrimental effect of the boredom resulting from continuous confrontation by the tasks might not have developed to the extent that would very likely be the case with longer duty periods. Although one cannot rule out the possibility that performance was depressed by the short sleep periods, the control data (4-work, 4-rest, 4-work, and 12-rest) tend to contradict this hypothesis. Sleeplessness periods during these schedules are better tolerated than in 4/2 schedules especially for tasks requiring sustained attention (5). Performance returns to approximately the level that would be expected had there been no period of sleep loss after the subjects on the 4/4 schedule had had two sleep periods (8 hours of sleep - 12 hours by the clock) and those on the 4/2 schedule had had three sleep periods (6 hours of sleep - 14 hours by the clock).

Superficially, it would appear that a schedule should be selected that would require the man to perform only during the high portion of his daily curve of activation. This would, in theory, provide on the order of 10 to 12 hours per day of "high-level" performance. However, examination of the industrial literature as well as laboratory and field research related to military operations suggests that ten hours represent too long a period of work at one stretch to expect performance to be maintained without at least an increase in the probability of errors and/or decrements.

Non-Temporal Factors

Non-temporal factors affecting the WRS cycle include:

1. The number of crew members on board.
2. The duty assignments or responsibilities of each crew member.
3. The need for time sharing of work space and facilities.

4. The need for equal division of task loading, rest and sleep time.
5. The need for completion of all tasks.
6. Emergency situations.

These non-temporal factors will probably dictate the initial WRS cycles on the first orbital lab flights. The best WRS cycle will be one adjusted to duties, independent of the ambient sun-shadow cycle (i. e., the earth-orbital space environment) and not necessarily corresponding to the time pattern of the earth day-night cycle. This non-24-hour cycle should be one to which the astronaut should be able to adapt in a reasonable amount of time and with which he can maintain synchronization of his metabolic clock to ensure his best psychological performance.

The use of shorter work periods provides an advantage in the event that an unusual requirement for man-hours should arise either because of a particular feature of a mission segment or because of an emergency (62, 147). That advantage would be realized during the period in which the system is "recovering" from the increased demand. Specifically, the man may have suffered a period of partial or even total sleep loss while coping with an emergency. Should that have been the case, he probably would find it substantially easier to maintain a satisfactory degree of alertness for a 4-hour duty period as compared to, for example, a 10-hour period until such time as he regains his pre-emergency status. Preliminary studies suggest that subjects in a 16/8 schedule tend to tolerate sleep deprivation for 2 days (on day 6 and 7) and recover faster than subjects on 4/2 and 4/4 work/rest schedules (147).

To the extent that a high level of performance will be required on what will approach a twenty-four hour per day basis, then serious consideration must be given to the selection of the work-rest schedule. The duration of the duty periods should be limited to a figure that will preclude the development of task-specific fatigue or boredom. With the anticipated exposures to the tasks to be on a day-after-day basis, a work period that seems to be suitable at the beginning of a mission may become intolerably long after a period of several weeks or months. This requires specific study. In addition, sleep periods should be arranged so that they will come at essentially the same time each day so that adjustment to (or in) the circadian rhythms will be facilitated. These two factors considered together imply a trade-off between the necessary or desirable duration and numbers of sleep periods and the duration of the individual duty periods.

The general conclusion reached from these past studies is that man is fairly well accustomed to a sleep-wakefulness cycle of a 24-hour duration and that he had diurnal variations in both performance and physiological functioning that coincide with this rhythm. When an atypical cycle is imposed, his physiological rhythms may be expected to show some adaptation to the non-24-hour periodicity--but adaptation is not likely to be complete nor to be uniform for all individuals. Concomitant decrements in performance, however, may not occur, especially if the sleep-wakefulness ratio is held constant. The performance decrement, whatever its degree, precipitated by the imposition of a typical work-rest-sleep cycle can be minimized in the following ways:

- The ideal solution is to avoid any non-24-hour work-rest-sleep cycle (i. e., use 8-on, 16-off).
- Where this is impossible, employ pre-flight, pre-synchronization periods for crews using the non-24-hour cycle proposed for that flight.
- Coordinate pre-flight pre-synchronization with the abilities of the individual crew members to adapt (those who adapt least well should be kept close to their typical schedule).
- Drugs may be utilized as a useful, but undesirable, tool if synchronization is found to be difficult, but more information is required on drug influence on cyclical phenomena.
- Local (orbital) adaptation to a typical cycle can be accomplished by new crew members as they are rotated to the lab (if they are not required to go on duty immediately upon arrival).

Further experimentation with various combinations of non-24-hour cycles in the weightless environment may yield additional, useful information.

Ground controllers and other operations personnel are often faced with asynchronous patterns during unusual work schedules or when flying to duty posts across several time zones (95, 152, 153, 199, 200, 267, 314, 315, 337). The asynchrony in both east to west and west to east flights produce subjective fatigue and temporal changes in heart rate and body temperature, but significant physiological deficit has been found only in the east to west flights. North-south flights do produce fatigue, but do not show asynchronous physiological patterns along with the psychological deficits (154). The duration of fatigue is usually shorter than the time lag in physiological phase shifts. Large inter-individual differences are noted with some individuals requiring up to 5 days for phase shift after Oklahoma City to Tokyo jet flights. Older individuals appear more subjectively sensitive to the asynchrony than younger ones. First, if a traveler to a distant location requires full alertness for a certain occasion he should, if possible, travel to his destination several days in advance, so that he will be adjusted to the new locality before he is called on to perform his tasks. Secondly, a coordination of the physiological with the physical day-night cycle can be achieved by presetting his physiological clock; i. e., by adopting 3 to 5 days in advance of the trip, a sleep and wakefulness pattern which corresponds to the physical day-night cycle of the place of destination (315).

Sleep Depth and Deprivation

The general sleep requirements in space operations were covered above. Depth of sleep can be measured by electroencephalographic techniques. Wave patterns can be distinguished for the awake state, eyes closed and the four stages of increasing depth of sleep (76, 365). The physiological basis for these patterns as well as oculomotor patterns are under study (187, 188, 211, 226, 268, 269, 279, 320, 347). As noted above, sleep patterns recorded in the first 51 hours of orbital flight are similar to those on earth. Irregular and aperiodic fluctuations in depth of sleep are normal occurrences (41, 76). They are often associated with dream states (76, 150, 166, 211,

229, 274, 306).

An electroencephalographic study of sleep was carried out in Gemini VII (42, 190). Baseline, multi-channeled EEG and other psychophysiological data were recorded on Borman during all stages of sleep and the working state on earth and compared with those in flight. Fifty-four hours of inflight data were obtained at which time the scalp electrode was dislodged. Eight hours after liftoff the command pilot closed his eyes and remained quiet for almost 2 hours without showing signs of drowsiness or sleep.

"The first inflight sleep period showed marked fluctuations between light sleep and arousal, with occasional brief episodes of stage 3 sleep for the first 80 minutes. At that time stage 4 sleep was reached, but in less than 15 minutes abrupt arousal and termination of sleep occurred.

On the second day, at 33 hours and 10 minutes after lift-off, the command pilot again closed his eyes and showed immediate evidence of drowsiness. Within 34 minutes he was in the deepest level of sleep (stage 4). During this prolonged period of sleep, there were cyclic alterations in level similar to those which occur in this astronaut during a full night of sleep under normal conditions. Generally, each successive swing toward deeper sleep, after the first period of stage 4 has been obtained, only reaches successively lighter levels; but, in Borman's second night of sleep, stage 4 was reached and maintained for 20 minutes or more at three different times after the first episode. It is interesting to speculate as to whether this increase in the number of stage 4 periods reflected an effect of deprivation of sleep during the first 24 hours.

After approximately 7 hours of sleep, a partial arousal from stage 4 sleep occurred, and, after a brief period (12 minutes) of fluctuating between stages 2 and 3, Borman remained in a state fluctuating between drowsiness and stage 1 sleep until finally fully roused about 1.5 hours later. Whether any periods of so-called "paradoxical" sleep, rapid eye movement sleep, or dreaming sleep occurred during this oscillant period cannot be determined with certainty from these records because of the absence of eye movement records and because paradoxical sleep is generally very similar in its character to ordinary stage 1 sleep. However, two periods of a pattern which resemble an admixture of certain characteristics of stage 1 and stage 2 sleep, and which resemble some of the activity which this group and other investigators have observed in paradoxical sleep, were recorded for relatively long periods in the second day's sleep (at 11:05 G. M. T. and 14:20 G. M. T.) (187, 188). These consist of runs of 3 per second "saw-tooth" waves, runs of low-voltage theta and alpha activity, low-voltage beta activity without spindles, and occasional slow transients with a time course of about 1 second."

For further study of sleep and other neurological phenomena, data banks of EEG taken on the astronauts are available (113, 341).

One must also consider sleep deprivation. This acute or chronic stress is accompanied by only a few consistent physiological changes (114, 118, 210, 326). The only marked changes consistently found are those that occur in neurological testing and in the electrical activity of the brain with increased convulsive tendency (14, 27, 31, 186, 275, 329). Decrease in pulse rate is not always found (254, 310). Blood sugar, hemoglobin, red and white cell count, excretion of 17-ketosteroids, total nitrogen and creatine, and the level of adrenal-like substances in the blood may be unchanged (328). Bioenergetics may be altered at a biochemical level (114). Body weight, blood pressure, hand steadiness, auditory acuity, depth perception, and dark adaptation also have shown no significant changes as a function of sleep loss (87). Only after 46 hours of sleeplessness has minor decrement been noted in visual acuity, muscle balance and stereoscopic function (256). After 5 hours of sleep, a return to normal was noted. Factors in the repayment of sleep debt have also been studied (98, 347). Specific deprivation of paradoxical and other stages of sleep are now under study (186, 187, 367).

Changes in estimates of fatigue have been reported, but marked differences in subjective factors among some of the studies prevent the drawing of direct conclusions (13). Correlation with performance degradation is variable. A moderate correlation has been reported between feelings of fatigue and the performance of mental multiplication (12). Correlations have also been found between a subject's estimation of fatigue and his actual performance of vigilance, interpretive, and grid-matching tasks (105, 106, 351). In contrast, air traffic controllers, on the job, developed feelings of weariness with sleep deprivation. These were not accompanied by performance decrements (293). There are also indications that judgements based on the appearance of a subject do not necessarily correlate with the subject's performance. Changes in behavior, personality, and physical appearance resulting from a 50-hour period of sleep deprivation have been found more pronounced than would be suggested by any performance decrements observed (63). A number of investigators have reported that increased irritability is among the first signs of pilot fatigue (80, 82, 215). Psychotic hallucinatory and regressive behavior is often brought about especially when confinement and isolation are superimposed on sleep deprivation (6, 101, 118, 277, 352). The symptoms appear to be related to the specific phase of sleep being deprived (367). Stage 4 deprivation produces depressive responses; stage 1-REM, irritability and emotional lability.

Of interest to contingency planners and commanders is the sequence of progressive deterioration of performance as sleep deprivation is prolonged. A review of this pattern has been made from which the following is taken directly (326). Following denial of one night's rest, detection of visual targets deteriorates markedly (364); choice behavior demands more time and exhibits more error (363); reading rate decreases although comprehension does not (170). Visual blurring and diplopia are accompanied with the beginning of misperception (364, 366), and where learning of a complex mental task is still taking place, the increment is reduced (60).

As the sleepless period begins to involve longer periods, effects are reported when noted. Thus, after 40 hours, mental work in arithmetic and color naming appear to suffer (344), as do ability to recall names and objects

from recent conversation. After 50 to 65 hours, momentary hallucinations are reported (364). Critical flicker frequency and speed of manual and leg movement decrease after 60 hours with the diurnal pattern of coordination and travel movements persisting, indicating some more basic physiological determinant (146). Memory as represented in the ACE test of intelligence, deteriorates after 72 hours. Serious lapses now seem to appear with the deterioration in function reflecting the involvement of or dependence upon alertness and sensory checking (363, 366). It seems that the performance and sensory deficit has been established by about 65 hours, for no appreciable drop is noted in these factors, temporal disorientation, or cognitive organization after that period (364). As one passes this three-night period, the personality factors reflect perceptual changes or deterioration as manifest in emotional disturbances (50), which seem to predominate until psychotic episodes (persecutory) appear after 120 hours without sleep (364).

Several studies have demonstrated decreases in performance as the cumulative effects of sustaining slightly reduced daily sleep over prolonged periods of time. Measures of performance and muscle tonus have been compared as they were affected by four successive periods of nightly sleep -- 4, 10, 8, and 6 hours, respectively--repeated 7 times over an interval of 28 days (111). Greater work output was accompanied by greater tonus, and muscle tonus appeared to vary more with sleep loss than did performance. This suggests the presence of some form of tonic muscular compensation during performance testing. Also, the cumulative effects of prolonged sleep loss tended to offset the efficacy of the tonic muscular compensation. The experimental effects in this study, however, were confounded, to a degree, by the different durations of sleep allowed on each day of every replication. This was particularly noticeable in the scores that followed 10 hours of sleep because they more nearly approximated those following the 4-hour sleep period than those following the 6- or 8-hour sleep periods. Since the 10-hour sleep period was always preceded by the 4-hour, it is very likely that a carry-over effect was present.

A schedule of 7 consecutive hours of nightly sleep during one month has been compared with an experimental schedule of interrupted nightly sleep during the following month (173). On each night of the experimental month the subject slept 3 hours, remained awake 3 hours, and then slept 3 additional hours. No difference in performance was found between the two schedules; in those tests where learning was present, improvement continued at the same rates regardless of the alternation-of-sleep routine.

In another study two "capable and highly motivated" subjects were required to perform continuously without sleep for a period of 24 hours (120). The task situation was a complex one that required the constant attention of each subject. The tasks, enclosed in two "flight" simulators, were selected to measure eye-limb coordination, problem solving, estimation of closure rates, selection and manipulation of controls, and the noticing of environmental changes both inside and outside the simulator. As indicated by each of the seven specific measures used, performance followed a pattern of rising to a peak after 6 to 10 hours and then dropping off sharply to a low point reached during the final 2 or 3 hours of the test. Differences between the two subjects and among the several tasks used were also quite evident. End-spurt effects

were avoided by slowing the subjects' clocks so that after 24 hours had actually elapsed, the clocks indicated that the subjects still had about 3 hours to work.

The vigilance performances of subjects who had just returned from flying 15-hour sorties at night have been found to be surpassed by those of otherwise comparable subjects who had just flown the same sorties during the day (104). Although this decrement may be interpreted as being a function of the loss of sleep, it may also be interpreted as being the result of differences in the difficulty of day versus night flying.

Motivation, monotony, complexity of task, arousal factors, and many other variables control the degradation of performance of the sleep deprivation (39, 40, 68, 87, 118, 326, 347, 352, 362, 366). Specific periods of sleep are more sensitive than others to behavioral and other responses of deprivation (367). Sleep deprivation of different forms will alter performance when superimposed on individuals in the process of adapting, or even fully adapted, to altered WRS cycles. Preliminary studies are discussed above.

Induction of sleep by electrical means has received study in recent years (33, 175, 176, 177, 183, 374). The advantage over drug-induced sleep is reversibility. However, techniques are still in the preliminary stage of development. Under some emergency situations on long duration flights, such techniques may be of value. Anesthesia may also be induced electrically (175, 177, 180, 183, 198, 299, 300, 359). Learning and memory during natural sleep are under study (32).

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